PHYSICS OF THE SPACE ENVIRONMENT

PHYS/EATS 3280

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Notes Set 6

Ionospheric Electron Densities – The D, E, F1 and F2 Layers

With the advent of radio communication in the early part of the last century it soon became clear that long distance communication was possible only because the radio waves were being reflected by layers in the upper atmosphere. Reflection and scattering of electromagnetic radiation requires the presence of free electrons and therefore layers of ionization must exist in the part of the atmosphere that then became known as the ionosphere. Studies using pulses of radio waves at different frequencies and measuring the time between the generation of the pulse and its echo indicated that there were several layers of ionization at different heights in the atmosphere. Such an *ionogram* is shown in Figure 6.1 where three distinct layers can be observed. The higher layers are not seen at the lower frequencies since the radio waves cannot penetrate the lower layers. The height at which a wave of a given frequency is reflected is determined by the electron density and occurs at some critical frequency.

This in principle allows a profile of electron density to be constructed from the *ionogram* using the relation $[f_N(\text{kHz})]^2 = 80.5\ n_e\ (\text{cm}^{-3})$, where f_N is the critical frequency and n_e is the electron density.

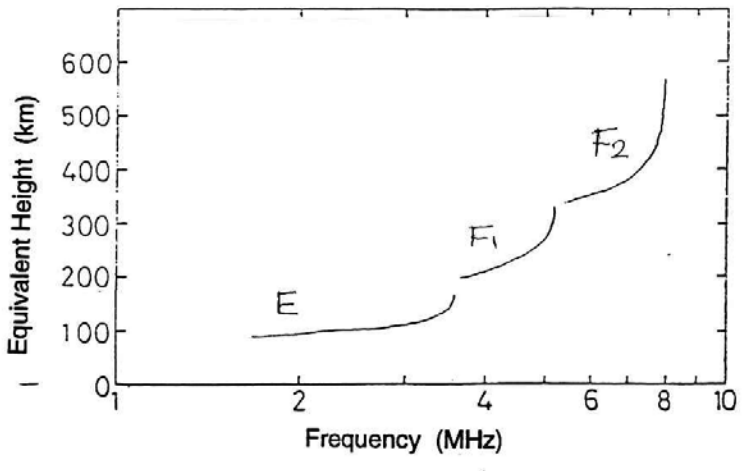

Fig. 6.1 Simplified daytime ionogram.

The *ionosonde* method of investigating the ionosphere leads to the conclusion that the various layers are distinct, but this is not really the case. Rocket measurements of electron density show a continuous profile with inflections corresponding to the radio layers. Figure 6.2 illustrates this and identifies the main ions in the various regions.

The main regions can be summarised as follows:

D region: 60 -90 km, $n_e \sim 10^2 - 10^4$ by day

E region: 105-160 km, $n_e \sim$ several x 10^5 by day

F region: > 180 km, $n_e \sim$ up to several x 10^6 at peak of the day, factor 10 less at night, maximum ~ 300 km but variable.

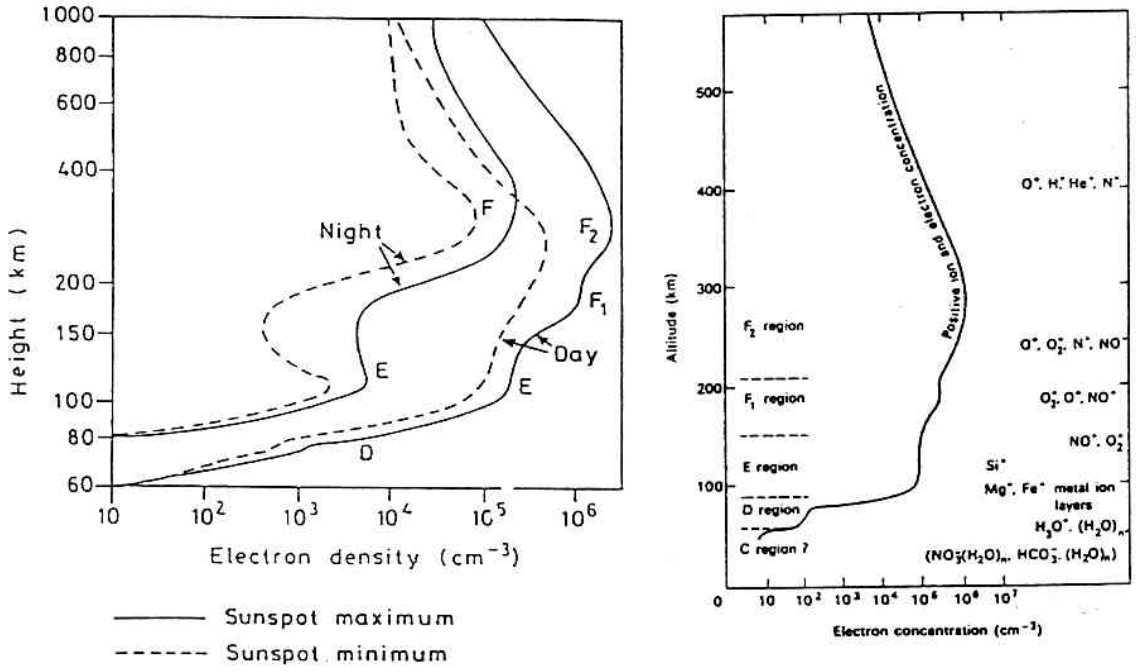

Fig 6.2. Typical vertical profiles of electron density in the mid-latitude ionosphere and the main ionic species.

Photochemical Principles Involved in the Formation of Ionospheric Layers

The ionosphere results from the interaction of solar radiation with the constituent gases. Photons of sufficient energy, when absorbed, have the possibility of ejecting an electron from the absorbing atom or molecule. The minimum energy required is the ionization energy for the species. Table 6.1 lists the ionization potentials for typical constituents in the upper atmosphere as well as the equivalent maximum wavelength that a photon may have if it is to be able to ionize it. It is clear that all of the threshold wavelengths lie in the extreme ultra violet (EUV, 17 - 175 nm) region of the spectrum where there are many

line emissions from ionized species in the solar *chromosphere* and *corona*. Since the radiation originates from these parts of the solar atmosphere it is subject to considerable variation in intensity during the solar cycle or during solar flares. The ionization efficiency for an atom is unity but for a molecule it is less that unity since a molecule has other ways of using up the energy *e.g.* by dissociating. The maximum production of ions at a given wavelength occurs at the altitude where the *optical depth* is unity in accordance with the Chapman theory. This height is given in Figure 6.3.

Table 6.1 . The ionization potentials and equivalent wavelengths for atmospheric gases

Constituent	Ionization Potential (eV)	λ_{max} (nm)
NO	9.25	134.0
O_2	10.08	102.7
H_2O	12.60	98.5
O_3	12.80	97.0
H	13.59	91.2
O	13.61	91.1
CO_2	13.79	89.9
N	14.54	85.3
H_2	15.41	80.4
N_2	15.58	79.6
Ar	15.75	78.7
Ne	21.56	57.5
He	24.58	50.4

The loss processes that remove electrons and bring electron production and electron loss into balance at steady state are of three main types:

radiative recombination: $e + X^+ \rightarrow X + h\nu$

dissociative recombination: $e + XY^+ \rightarrow X + Y$

and *three-body electron attachment*: $e + Z + M \rightarrow Z^- + M$

Typical recombination coefficients for the first and second processes are 10^{-12} and 10^{-7} $cm^3\ s^{-1}$ respectively.

The E and F1 Regions

The E-Region

The central part of the ionosphere is made up of the E-region with a peak at around 105 km and the F1-region where the maximum electron density occurs between 160 and 180 km. The E region is formed by the absorption of the more penetrating part of the EUV spectrum between 80 and 100 nm and by X-rays between 1 and 10 nm wavelength.

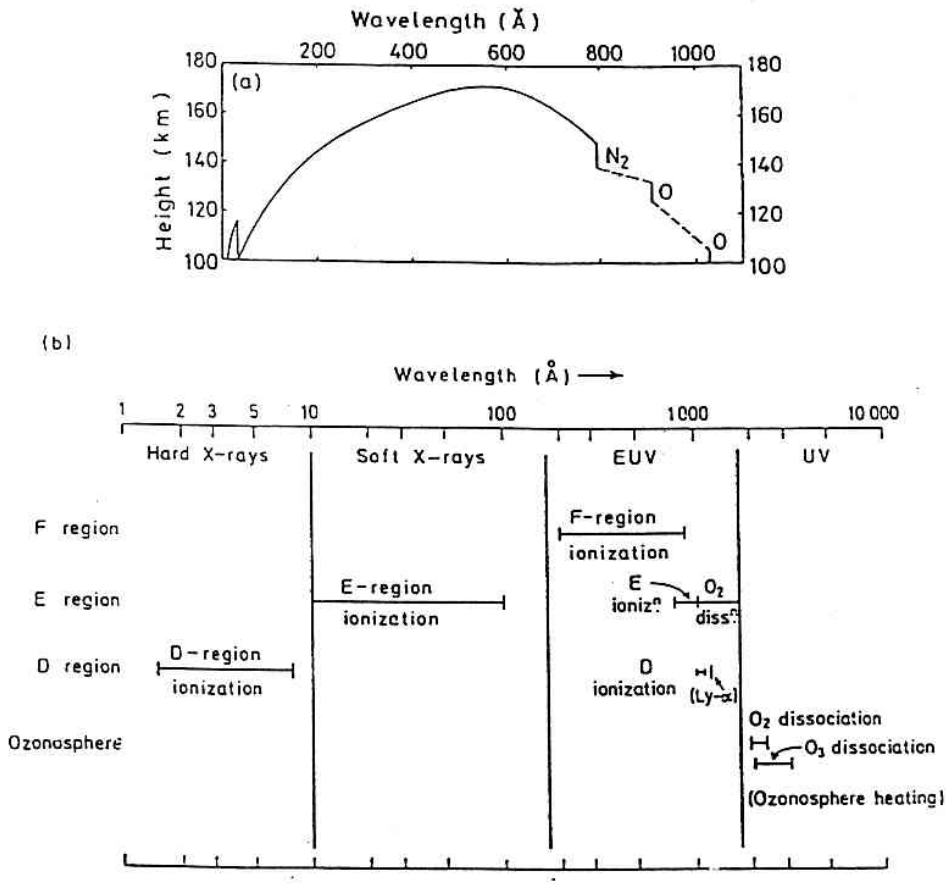

Fig. 6.3 (a) The height of unity optical depth. (b) The role of various solar emissions in the upper atmosphere.

The EUV is absorbed by O_2 to form O_2^+ while the X-rays ionize all the constituents to form N_2^+, O_2^+ and O^+. The X-ray contribution is relatively small at least for solar minimum conditions. Through various charge exchange reactions the most abundant ions become NO^+ and O_2^+. The major loss processes are then *dissociative recombination* of these major ions - NO^+ and O_2^+. Since *radiative recombination* is very slow and since the pressure is too low for *three-body electron attachment* to be important, the dominant electron loss reactions in the E-Region are the *dissociative recombination* processes

$$\left.\begin{aligned} e + O_2^+ &\rightarrow O + O \\ e + NO^+ &\rightarrow N + O \end{aligned}\right\} \qquad (1) \qquad k = k^{eff}$$

The F1-Region

In the F1 region, most of the ionization is caused by EUV radiation between 20 - 90 nm producing mostly O^+ ions but also N_2^+, O_2^+, He^+ and N^+. The O^+ ions are rapidly converted to molecular ions via reactions of the form

$$\left.\begin{aligned} O^+ + O_2 &\rightarrow O_2^+ + O \\ O^+ + N_2 &\rightarrow NO^+ + N \end{aligned}\right\} \quad (2)$$

The dominant F1-region ions are therefore O_2^+ and NO^+ with the reaction $N_2^+ + O \rightarrow NO^+ + N$ also making a contribution. As in the E-region, the loss is dominated by *dissociative recombination* with the dissociative recombination reactions (1) being '*rate limiting*' rather than the initial F1 *charge exchange* reactions (2).

E- and F1-Region Electron Densities

In both the E- and F1-regions the electron loss rates are dominated by dissociative recombination of O_2^+ and NO^+ and so the electron loss rates are given by

$$dn_e/dt = k^{eff}[A^+]n_e$$

where $[A^+] = \{[O_2^+]+[NO^+]\}$. But since we have general charge neutrality,

$$[A^+] = n_e$$

so that

$$dn_e/dt = k^{eff} n_e^2$$

Now, recognizing that the Chapman ion production rate was given by

$$q(h,\chi) = q^o_{max} \exp[1-z-\sec \chi \exp(-z)]$$

with $z = (h-h^o_{max})/H$, then at steady state we expect the E- and F1-region electron densities given by

$$n_e(h,\chi) = (q^o_{max}/k^{eff})^{1/2} \exp[0.5\{1-z-\sec \chi \exp(-z)\}]$$

where $z = (h-h^o_{max})/H_{O2}$ in the case of the E-region and $z = (h-h^o_{max})/H_O$ in the case of the F1-region.

Therefore, the E- and F1-Region electron (and positive ion) density profiles are well represented by Chapman layers, and apart from the factor of 0.5 in the outer exponential, the E- and F1-region electron density profiles will exhibit most of the diurnal, latitudinal, seasonal and solar cycle characteriscs previuosly ascribed to the Chapman ion production rates.

Figure 6.4 shows an F1 electron density profile calculated using the Chapman function. The dashed line shows the O^+ ion production rate (per unit solar flux) calculated for atomic oxygen with a scale height of 50 km, an atomic oxygen density of $4x10^{11}$ cm^{-3} at 100 km, an average ionization cross section of $4x10^{-18}$ cm^2 and a solar zenith angle of

χ=0. The solid line shows the corresponding F1 electron densities calculated for a solar flux of $1x10^{11}$ photons cm^{-2} s^{-1} and $k^{eff} = 1x10^{-8}$ cm^3 s^{-1}.

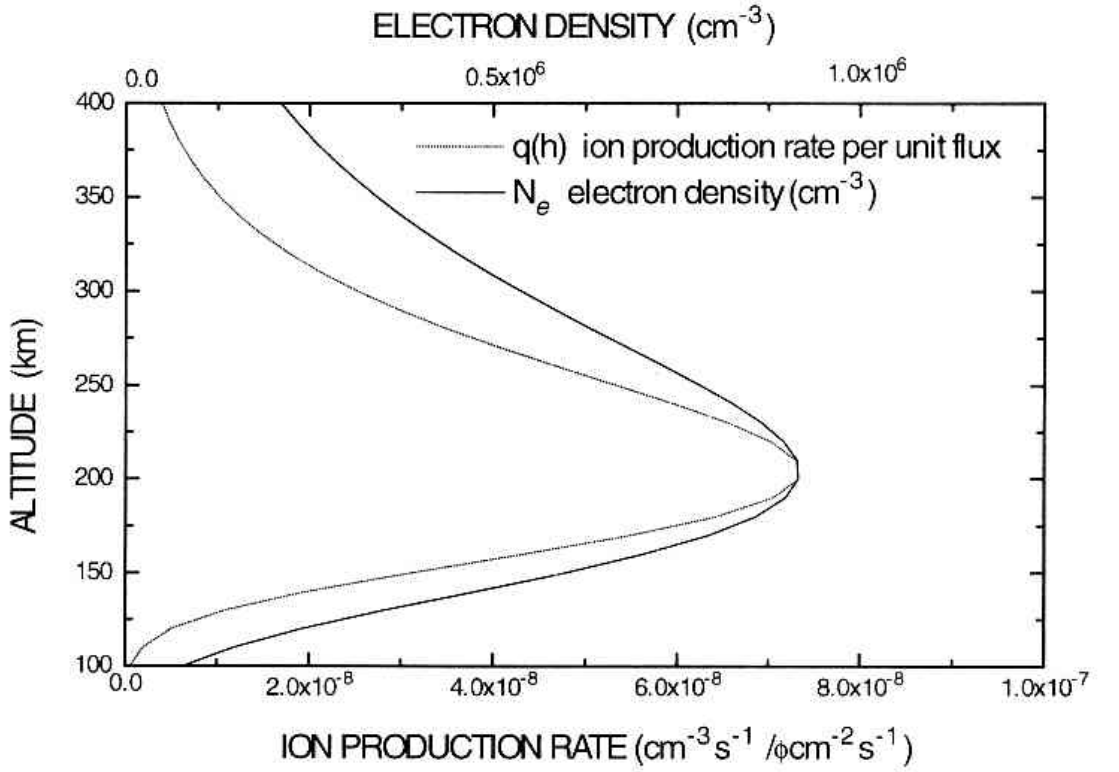

Fig. 6.4. Chapman modelled F1 ion production rates and electron densities

The F2 Region

The F2 region has no peak in electron production to account for it rather the maximum arises because of the interplay between production and loss processes as well as transport. Here the major ion produced is O^+ so that the production $q \propto [O]$ while the loss process is two-step involving first $O^+ + N_2 \rightarrow NO^+ + N$ and then dissociative recombination of NO^+. At these heights the concentration of N_2 is so low that the first stage becomes rate limiting i.e. the loss $\propto [N_2]$ so that in equilibrium

$$\left.\begin{aligned} N_e &\propto [O]/[N_2] \propto \exp\left[-\frac{h}{H(O)} + \frac{h}{H(N_2)} \right] \\ N_e &\propto \exp\left[-\frac{h}{H(O)}\left(1 - \frac{H(O)}{H(N_2)}\right)\right] = \exp\left[+0.75\frac{h}{H(O)}\right] \end{aligned}\right\} \qquad (3)$$

because the masses of N_2 and O are in the ration 1.75:1. Thus the electron density increases with height because the loss rate falls off more rapidly than the production rate. The maximum occurs when diffusion which increase with decreasing density becomes so rapid that the ions come into diffusive equilibrium and the electrons are forced to follow along. It should be noted that the scale height for the electron-ion pairs is twice that for a neutral of the same mass since the electrostatic force requires that the two particles act as a pair with a mass that is $(m_i + m_e)/2 \approx m_i/2$.

Thge F2 Layer is, therefore, not a true Chapman layer – rather it just resembles a Chapman layer by accident.

The D region

The D-region is a part of the ionosphere not explained by the Chapman-like E-region processes described above. The D-region is dominated by a different chemistry distinguished by (a) positive ion conversion to large protonated water clusters, (b) conversion of the free electrons to negative molecular ions, and (c) the special roll played by the Lyman-α line of the solar spectrum which, because of a coincidental window in the O_2 absorption spectrum, is able to penetrate to below 70 km.

The four major sources of D-region ionization are :

Solar Lyman-α (121.5 nm) ionization of NO (the only component with a sufficiently low ionization potential)

EUV between 102.7 and 111.8 nm ionizing the $O_2(a^1\Delta g)$ state that is produced via ozone photolysis.

Hard X-rays of 0.2 - 0.8 nm ionizing all constituents

Cosmic rays ionizing all constituents.

Figure 6.5 shows the relative importance of these processes for day and night conditions where it is clear that it is the ionization of NO by Ly-α that is the most important.

N_2^+ produced by cosmic rays and hard X-rays is rapidly converted to O_2^+ through charge exchange with O_2.

One might expect then that, as for the E region, the major ions in the D region should be O_2^+ and NO^+.

However, a very complex sequence of ion-molecule reactions, which appear to dominate at the relatively high densities of the D-region, result in most of the positive charge ending up in the form of protonated water *'clusters'*, *i.e.*, $H_3O^+(H_20)_n$, with n normally between 2 and 5 but sometimes exceeding $n = 40$.

Another distinguishing feature of the D-region is the predominance of negative molecular ions as well as free electrons.

These negative molecular ions are formed by '*three-body attachment'* reactions such as

$$O_2 + e + O_2 \rightarrow O_2^- + O_2$$

The equilibrium D-region electron densities are then determined by a balance between the *three-body attachment* process which occurs night and day, and the *photodetachment* process

$$O_2^- + h\nu \rightarrow O_2 + e$$

caused by visible and near IR solar radiation during the sunlit hours

The resulting diurnal variation in the –ve ion to free electron density ratios that then result are shown in Figure 6.6.

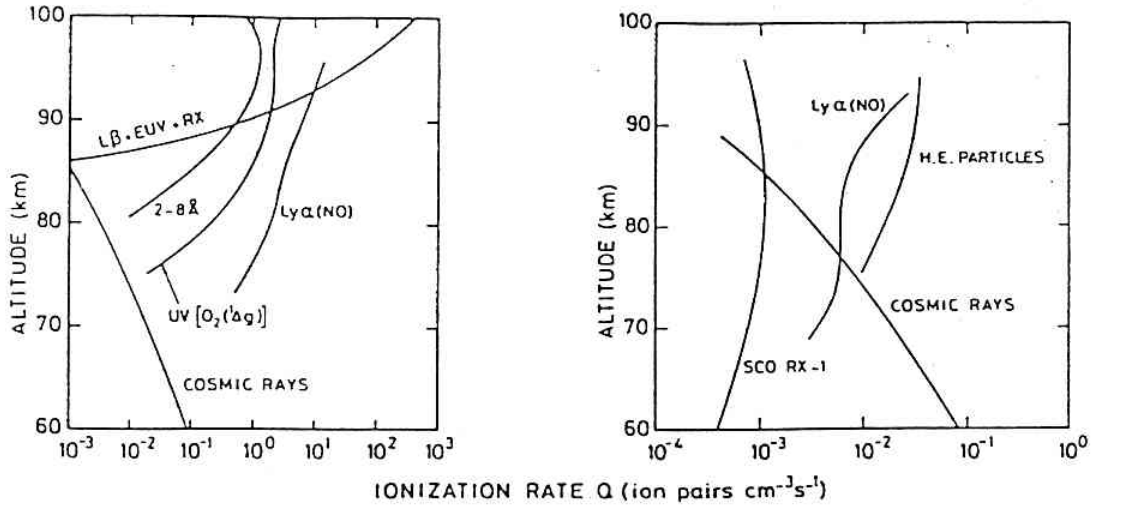

Fig. 6.5 : D region ionization rates resulting from various processes for day and night conditions at solar minimum.

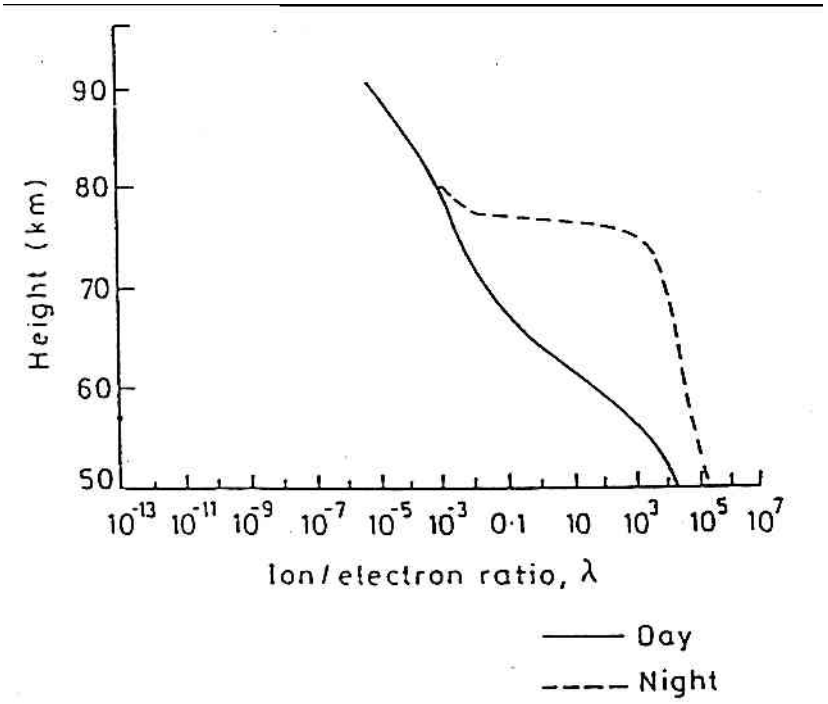

Fig. 6.6 The ratio of negative ions to electrons as a function of altitude for day and night conditions in the D-Region.