Atmospheric Physics

Lecture 12

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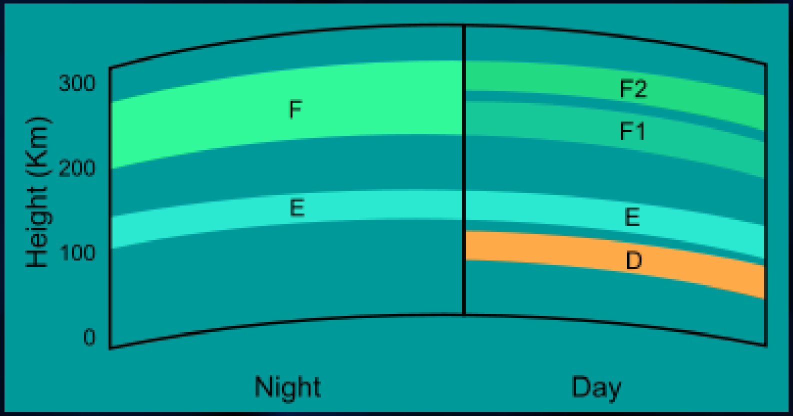
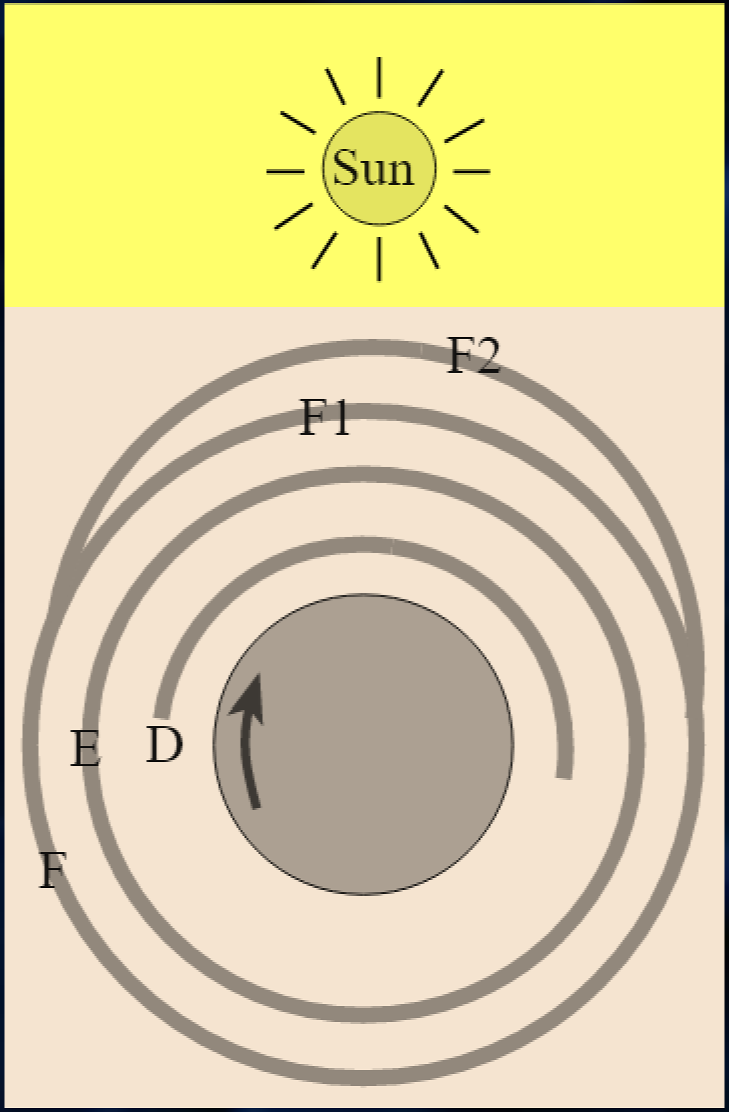
Primary Ionospheric Regions

Region	Altitude	Peak	Density
D	60-90 km	90 km	$10^8 - 10^{10}\ m^{-3}$
E	90-140 km	110 km	Several x $10^{11}\ m^{-3}$
F1	140-200 km	200 km	Several 10^{11}-$10^{12}\ m^{-3}$
F2	200-500 km	300 km	Several x $10^{12}\ m^{-3}$





Simplified view of the layers in the ionosphere over the period of a day

Ionisation

1) Photo-ionisation

$$A + h\nu \rightarrow A^*$$

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

$$\frac{dne}{dt} = q - L + T$$

Deionisation

1)

$$O^{+} + e^{-} \rightarrow O + h\nu(10ev)$$

$$A^{+} + e^{-} \rightarrow A + h\nu$$

2)

$$A^{+} + e^{-} + M \rightarrow A + M + h\nu$$

$$\frac{dne}{dt} = -\alpha.ne.n(A^{+})$$

$$\frac{dne}{dt} = -\alpha.ne^{2}$$

2) Detachement

a) Electron photo-detachment

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

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

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

$$\frac{dne}{dt} = \gamma'.n(A^-)$$

b) Electron detachment via collision

$$A^{-} + M \rightarrow A + M + e^{-}$$

$$\frac{dne}{dt} = \gamma . n(A^{-}) . n(M)$$

$$\gamma \simeq 10^{-15} - 10^{-16}$$

3) Attachment

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

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

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

$$\frac{dne}{dt} = -b.ne.n(A) = -\beta.ne$$

$$\frac{dne}{ne} = -\beta dt \rightarrow ne = ne_0 e^{-\beta t} = ne_0 e^{-t/\tau}$$

$$z = 100km \begin{cases} n(O_2) \sim 10^{12} \\ n(O) \sim 10^{12} \end{cases} \quad \begin{matrix} b(O_2) \sim 10^{-16} \\ b(O) \sim 10^{-15} \end{matrix} \quad \begin{matrix} \tau(O_2) = 10^4 \sec \simeq 3h \\ \tau(O) \sim 10^3 \sec \simeq 17 \min \end{matrix}$$

4) Recombination dissociation

$$xy^{+} + e^{-} \rightarrow x^{*} + y^{*}$$

$$xy + A^{+} \rightarrow xy^{+} + A$$

At night, recombination can result in the loss of the D region

$$O_2^{+} + e^{-} \rightarrow O + O$$

$$NO^{+} + e^{-} \rightarrow N + O$$

$$N_2^{+} + e^{-} \rightarrow N + N$$

$$\left[\frac{dne}{dt}\right]_L = -k_2.ne.n(xy^+)$$

$$\left[\frac{dn(A^+)}{dt}\right]_L = -k_1.n(A^+).n(xy)$$

$$according: \quad A + h\nu \rightarrow A^+ + e^-$$

$$\left[\frac{dn(A^+)}{dt}\right] = \left[\frac{dne}{dt}\right] = q$$

$$q = k_1.n(A^+).n(xy)$$

$$q = k_2.ne.n(xy^+)$$

we know $n(A^+) + n(xy^+) = ne$

$$\frac{q}{k_1 . n(xy)} + \frac{q}{k_2 . ne} = ne$$

$$q = \frac{k_1 k_2 . n(xy) . ne^2}{k_1 . n(xy) + k_2 . ne}$$

1) $k_1 n(xy) >> k_2 . ne \Rightarrow q = k_2 . ne^2$ *comparing with* $q = -\alpha ne^2$

2) $k_1 n(xy) << k_2 . ne \Rightarrow q = k_1 . n(xy) . ne = \beta ne$

comparing with $q = -\beta ne$

$$f \quad xy = o_2, \quad A = o$$

$$\begin{cases} O_2 + O^+ \rightarrow O_2^{\ +} + O + 1.53\ ev \\ O^+{}_2 + e^- \ \rightarrow \ O \ + O \ + 6.96\ ev \end{cases}$$

$$\begin{cases} O^+ + N_2 \rightarrow NO^+ + N + 1.09\ ev \\ N_2^{\ +} + O \ \rightarrow \ \mathrm{NO}^+ + N \ + 3.09\ ev \end{cases}$$

$$\begin{cases} NO^+ + e^- \rightarrow N + O + 2.76\ ev \\ N_2^{\ +} + e^- \ \rightarrow \ N + N \ + 5.02\ ev \end{cases}$$

1) Negative ions total changes Formula

$$A^{-} + A^{+} \rightarrow A^{*} + A^{*}$$

$$\frac{dn(A^{-})}{dt} = \alpha_i . n(A^{-}) . n(A^{+})$$

$$\frac{dn(A^{-})}{dt} = -\alpha_i . n(A^{-}) . n(A^{+}) + b . n(A) . ne - \gamma . n(M) . n(A^{-}) - \gamma' . n(A^{-})$$

$$\frac{dn(A^{-})}{dt} = 0$$

$$b . n(A) . n_e = \gamma . n(M) . n(A^{-}) + \gamma' . n(A^{-})$$

$$b.n(A) = \gamma.n(M).\frac{n(A^-)}{ne} + \gamma'\frac{n(A^-)}{ne}$$

$$\frac{n(A^-)}{ne} = \lambda$$

$$\lambda = \frac{n(A^-)}{ne} = \frac{bn(A)}{n(M)\gamma + \gamma'}$$

2) Electrons total changes Formula

$$\frac{d(ne)}{dt} = q - \alpha ne.n(A^+) - b.n(A).ne + \gamma n(A^-).n(M) + \gamma' n(A^-)$$

$$\frac{dn(A^-)}{dt} - \alpha_i n(A^-).n(A^+)$$

$$\frac{d(ne)}{dt} = q - \alpha.ne.n(A^{+}) - \frac{dn(A^{-})}{dt} - \alpha_i n(A^{-}).n(A^{+})$$

$$n(A^{+}) = n(A^{-}) + ne$$

$$n(A^{+}) = ne(\frac{n(A^{-})}{ne} + 1) = (1+\lambda)ne \quad *$$

$$\lambda = \frac{n(A^{-})}{ne} \rightarrow n(A^{-}) = \lambda ne \quad **$$

$$\frac{dn(A^{-})}{dt} = \frac{d(\lambda.ne)}{dt} = \lambda\frac{dne}{dt} + ne\frac{d\lambda}{dt} \quad ***$$

$$\frac{d(ne)}{dt} = q - \alpha(1+\lambda).n_e^{\ 2} - \lambda\frac{dne}{dt} - ne\frac{d\lambda}{dt} - \alpha_i\lambda(1+\lambda).n_e^{\ 2}$$

$$(1+\lambda)\frac{d(ne)}{dt} = (1+\lambda)\left[\frac{q}{1+\lambda} - (\alpha+\lambda\alpha_i)n_e^{\ 2} - \frac{ne}{1+\lambda}\frac{d\lambda}{dt}\right]$$

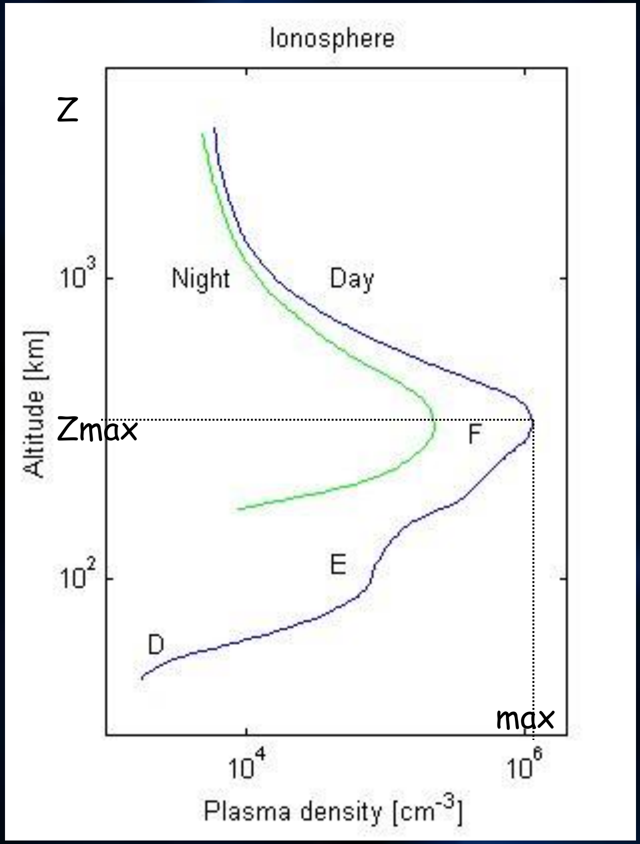
$$\frac{d(ne)}{dt} = q_e - \alpha_e.n_e^{\ 2}$$

$$ne = \left(\frac{q_e}{\alpha_e}\right)^{1/2} \qquad ne = \frac{q_e}{\beta}$$

Ionosphere layers formation theory

$$\frac{dne}{dt} = q - L + T$$

$$\frac{dne}{dt} = q - \alpha n_e^{\;2} - \beta ne$$



Transport

$$\frac{dne}{dt} = q - L + T$$

$$\frac{dn_e}{dt} = q - L - div(N\vec{V})$$

$$T = -\frac{d}{dz}(n_e.V_z)$$

$$\frac{dn_e}{dt} = q - L - \frac{d}{dz}(n_e.V_z)$$

Diffusion

$$F_z = -\frac{1}{N}\frac{dp}{dz} - mg$$

$$p = NkT \rightarrow \frac{dp}{dz} = kT\frac{dN}{dz}$$

$$F_z = -\frac{kT}{N}\frac{dN}{dz} - mg$$

$$F_z = ma = m\frac{dv_z}{dt} = \frac{dmv_z}{dt}$$

$$\Delta mv_z = F_z \Delta t$$

$$F_z = \frac{\Delta mv_z}{\Delta t} = \frac{mv_z}{t} = \frac{mv_z}{1/\nu}$$

$$\nu mv_z = -\frac{kT}{N}\frac{dN}{dz} - mg$$

$$v_z = -\frac{kT}{\nu m}\left(\frac{1}{N}\frac{dN}{dz} + \frac{mg}{kT}\right)$$

$$v_z = -\frac{kT}{\nu m}\left(\frac{1}{N}\frac{dN}{dz} + \frac{1}{H}\right)$$

$$H = \frac{kT}{mg}$$

$$N = N_0 e^{-Z/H}$$

$$D = \frac{kT}{\nu m}$$

$$v_z = -D\left(\frac{1}{N}\frac{dN}{dz} + \frac{1}{H}\right)$$

$$v_z = -\frac{D}{kT}\left(\frac{kT}{N}\frac{dN}{dz} + mg\right)$$

$$v_z = \frac{D}{kT} F_z$$

$$\frac{1}{H_i} = \frac{m_i g}{kT_i} \quad , \quad \frac{1}{H_e} = \frac{m_e g}{kT_e}$$

$$D_e = \frac{kT_e}{m_e \nu_e} \quad , \quad D_i = \frac{kT_i}{m_i \nu_i}$$

$$v_i \approx v_e \quad , \quad m_e \ll m_i$$

$$m_e v_e \ll m_i v_i \;\Rightarrow\; D_e \gg D_i \Rightarrow v_{ze} \gg v_{zi}$$

$$F_z = -\frac{kT}{N}\frac{dN}{dz} - mg - eE$$

$$F_z = -\frac{kT}{N}\frac{dN}{dz} - mg + eE$$

$$v_{ze} = -D_e\left(\frac{1}{N_e}\frac{dN_e}{dz} + \frac{1}{H_e} - \frac{eE_z}{kT_e} \right)$$

$$v_{zi} = -D_i\left(\frac{1}{N_i}\frac{dN_i}{dz} + \frac{1}{H_i} + \frac{eE_z}{kT_i} \right)$$

$$\left(v_z\right)_{e,i} = -D\left(\frac{1}{ne}\frac{dne}{dz} + \frac{1}{H_e} - \frac{eE_z}{kT} \right)$$

One-Fluid Theory

$m_e \quad , \quad q_e = -e \qquad\qquad m_i \quad , \quad q_i = ze$

$n = n_e = n_i \qquad\qquad J = 0 \qquad\qquad n_e v_e = n_i v_i$

$T_e = T_i = T$

$$\frac{eE_z}{kT} = -\frac{v_z}{D_e} - \frac{1}{H_e} - \frac{1}{N_e}\frac{dN_e}{dz} = \frac{v_z}{D_i} + \frac{1}{H_i} + \frac{1}{N_i}\frac{dN_i}{dz}$$

$$-v_z\left(\frac{1}{D_e}+\frac{1}{D_i}\right)-\left(\frac{1}{H_e}+\frac{1}{H_i}\right)-\frac{1}{N_e}\frac{dN_e}{dz}-\frac{1}{N_i}\frac{dN_i}{dz}=0$$

$$-v_z\frac{2}{D}-\frac{2}{H}-\frac{2}{n}\frac{dn}{dz}=0$$

$$(v_z)=-D\left(\frac{1}{n}\frac{dn}{dz}+\frac{1}{H}\right)$$

b) Formation of the F2 region

* key reactions

Photoionization:

$O + h\nu \rightarrow O^{+} + e^{-}$ (λ<911Å) (1) *

$N_2 + h\nu \rightarrow N_2^{+} + e^{-}$ (λ< 796Å) (2a)

$N_2^{+} + O \xrightarrow{(fast)} NO^{+} + N$ (2b)

$O_2 + h\nu \rightarrow O_2^{+} + e^{-}$ (λ< 1026Å) (3)

Dissociative recombination (rapid) :

$O_2^{+} + e^{-} \rightarrow O + O + h\nu$ (λ= 6300Å) "Airglow" (4) * $k_{O_2^{+}} \approx 3\times10^{-7} cm^{-3} s^{-1}$

$NO^{+} + e^{-} \rightarrow N + O$ (5) * $k_{NO^{+}} \approx 3\times10^{-7} cm^{-3} s^{-1}$

$N_2^{+} + e^{-} \rightarrow N + N$ (6)

$O_2^{+} + N(^4S) \rightarrow NO + O$ (7)

Radiative recombination (slow) :

$$O^+ + e^- \rightarrow O^* \rightarrow O + h\nu \quad (7774 \text{ Å}) \quad (8)$$

Charge transfer:

$$O^+ + O_2 \rightarrow O_2^+ + O \quad (9)$$

* $k_{O_2} \approx 2\times10^{-11} cm^{-3} s^{-1}$

$$N^+ + O \rightarrow O^+ + N \quad (10)$$

$$O_2^+ + NO \rightarrow NO^+ + O_2 \quad (11)$$

Ion-atom interchange:

$$O^+ + N_2 \rightarrow NO^+ + N \quad (12)$$

* $k_{N_2} \approx 1\times10^{-12} cm^{-3} s^{-1}$

$$N^+ + O_2 \rightarrow NO^+ + O \quad (13)$$

$$N^+ + O_2 \rightarrow O_2^+ + N(^4S) \quad (14)$$