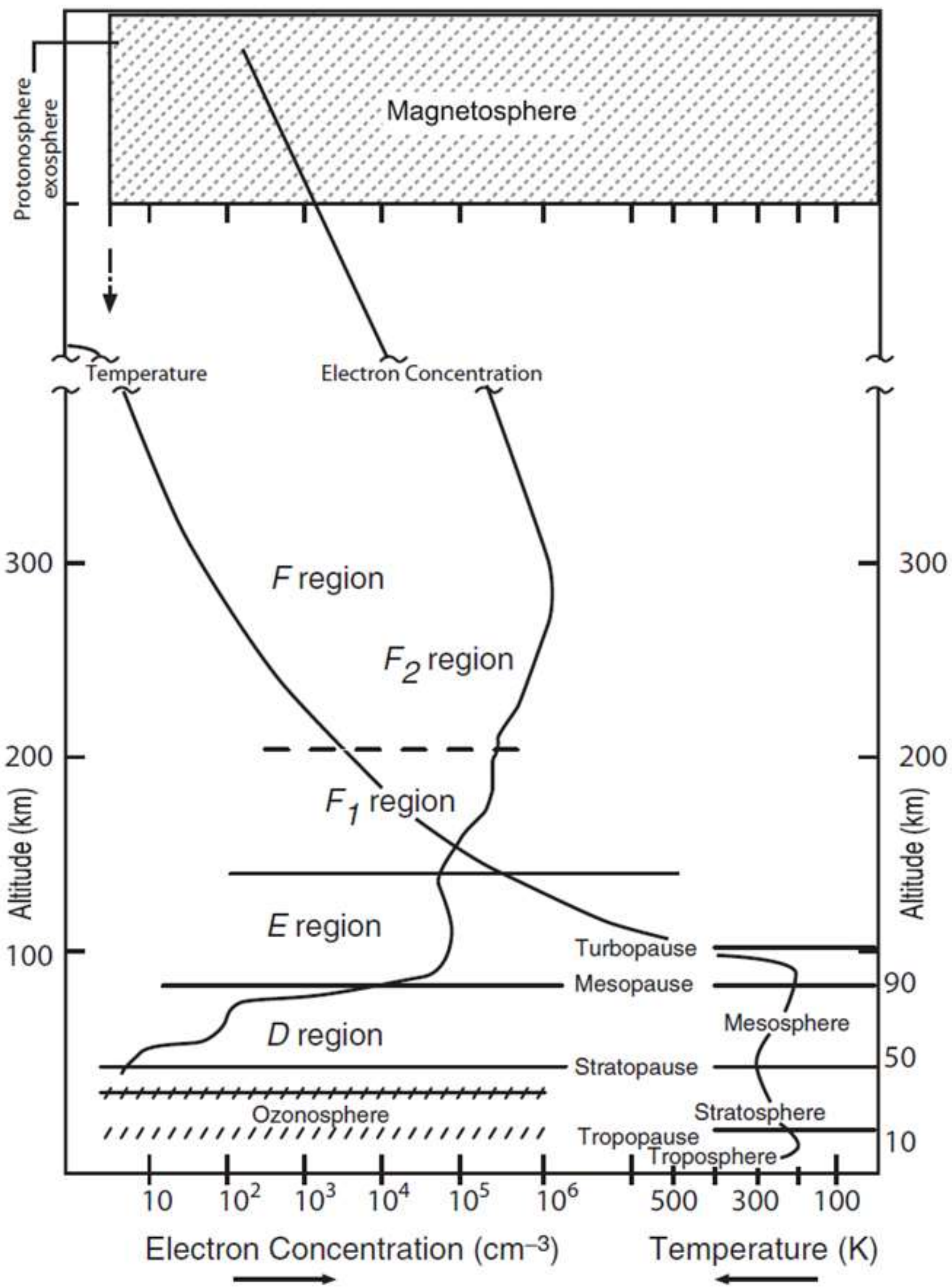
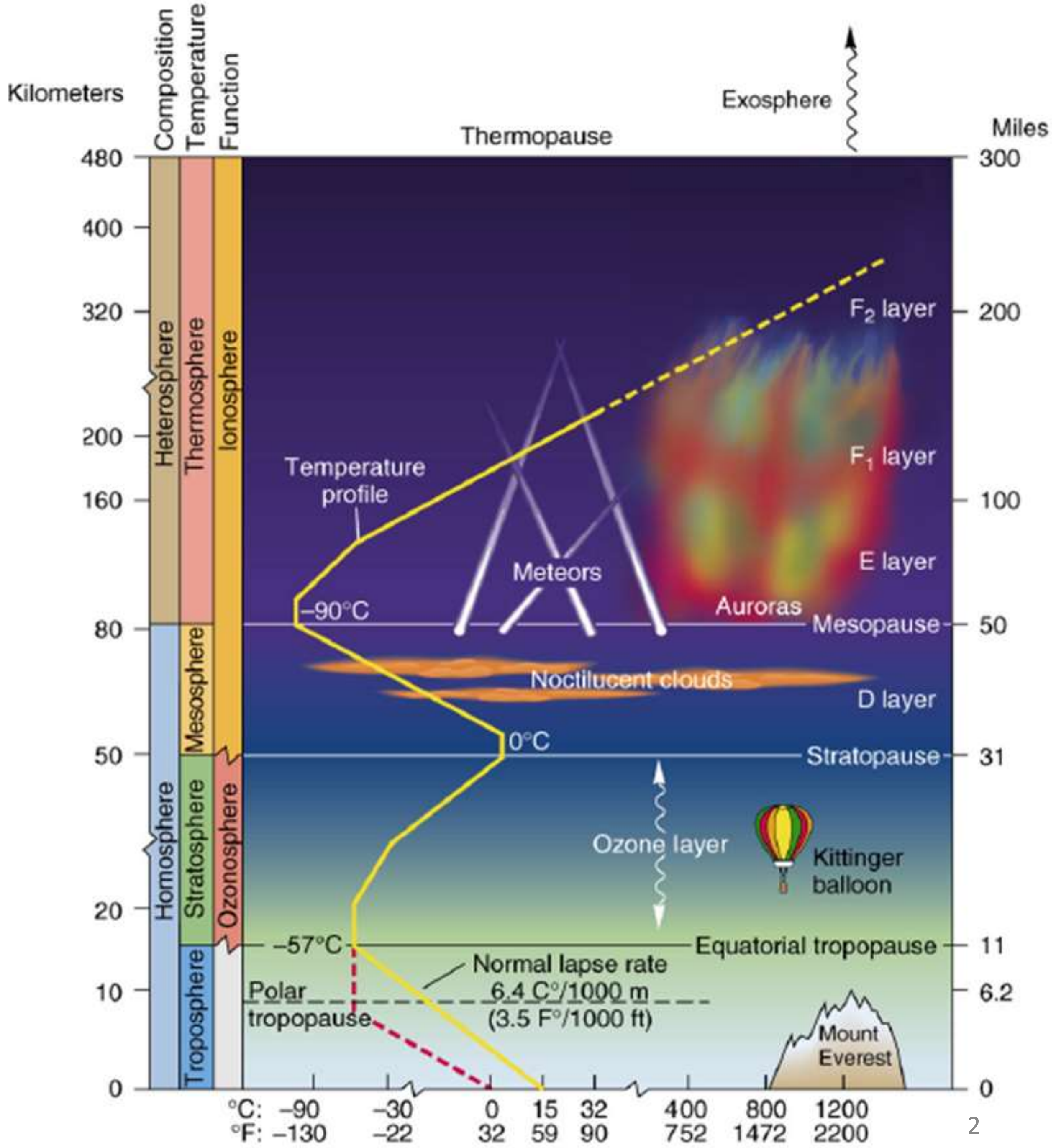
Formation of the ionosphere: photochemical equilibrium

Additional reading:
Rishbeth & Garriott book,
Intro to ionospheric physics, Ch. 3


Protonosphere exosphere
Magnetosphere
Temperature
Electron Concentration
F region
F2 region
F1 region
E region
D region
Turbopause
Mesopause
Stratopause
Ozonosphere
Tropopause
Troposphere
Stratosphere
Mesosphere
Altitude (km)
300
200
100
90
50
10
10 10² 10³ 10⁴ 10⁵ 10⁶
500 300 100
Electron Concentration (cm⁻³)
Temperature (K)


Kilometers
Composition
Temperature
Function
Exosphere
Thermopause
Miles
480
400
320
200
160
80
50
20
10
0
300
200
100
50
31
11
6.2
0
Heterosphere
Thermosphere
Ionosphere
Homosphere
Mesosphere
Stratosphere
Ozonosphere
Troposphere
F2 layer
F1 layer
E layer
D layer
Temperature profile
Meteors
Auroras
−90°C
Mesopause
Noctilucent clouds
0°C
Stratopause
Ozone layer
Kittinger balloon
−57°C
Equatorial tropopause
Normal lapse rate
6.4 C°/1000 m
(3.5 F°/1000 ft)
Polar tropopause
Mount Everest
°C: −90 −30 0 15 32 400 800 1200
°F: −130 −22 32 59 90 752 1472 2200

Sources of ionization

- Solar extreme ultraviolet (EUV).
- Solar X-ray radiation.
- Photons above 12 eV can ionise atmospheric components.
- Energetic particles from magnetosphere (e.g., auroras) can be important at high latitudes.
- Cosmic rays from galactic sources.

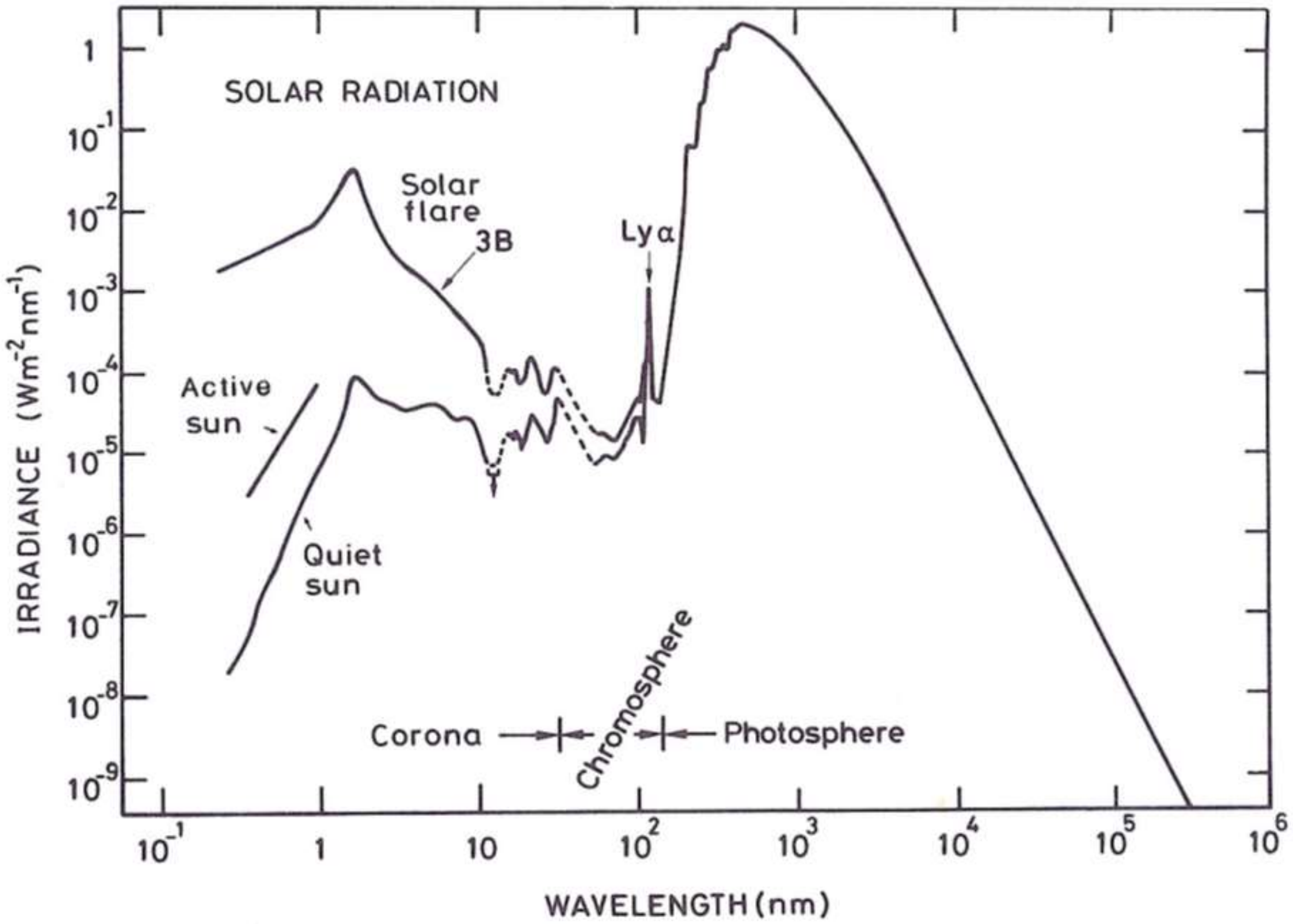
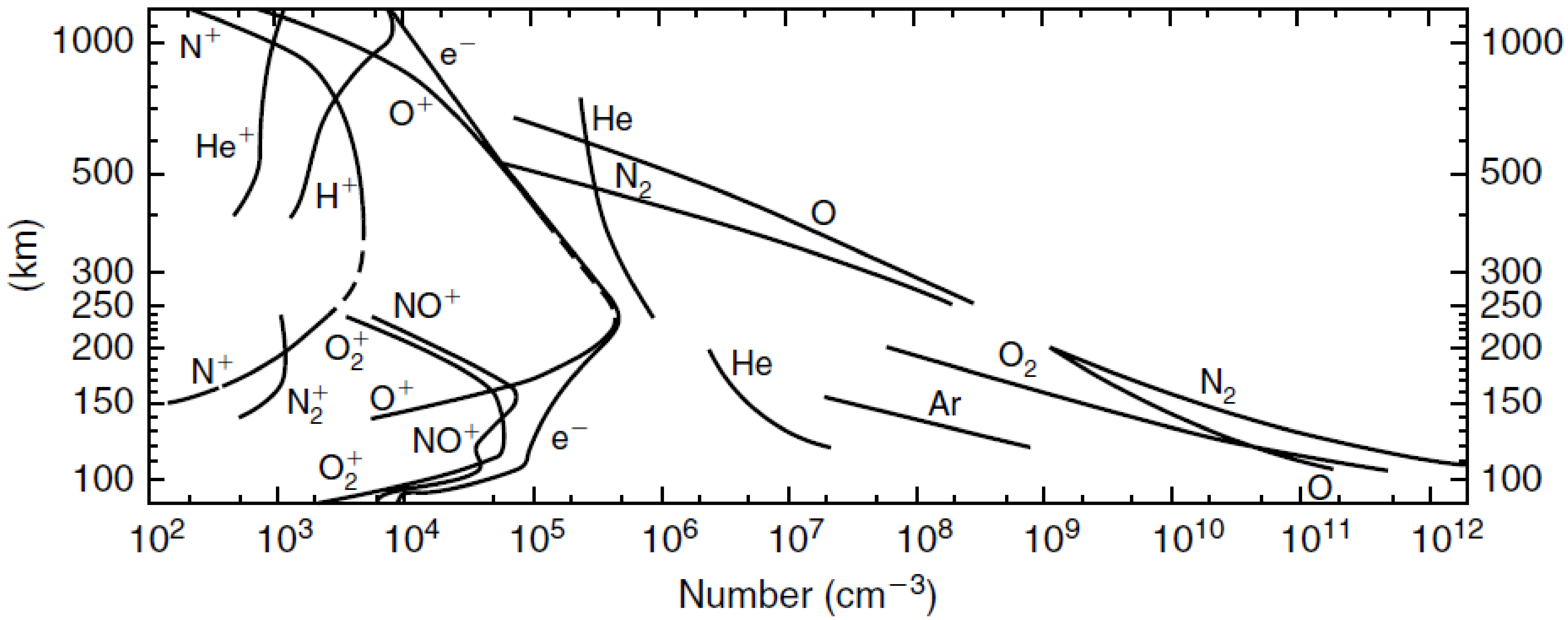


Fig. 4.5. Spectral distribution of the solar irradiance, and its variation with solar activity. The logarithmic representation emphasizes the contribution of x-rays and extreme ultraviolet radiation. After Smith and Gottlieb (1974).

Neutral and ionized components



Balance of ionization

Rate of change of electron concentration **=** Gain by production **-** Loss by destruction **-** Change due to transport

Continuity equation

$$\frac{\partial N}{\partial t} = q - l(N) - div(N\mathbf{V})$$

Below ~250 km the transport term is not important

Photochemical equilibrium: $q = l(N)$

Basic theory of photoionization

- The radiation is monochromatic, its photon flux $I(h)$
- Single absorbing gas, $n(h)$
- The atmosphere is plane and horizontally stratified

Production rate per unit volume:

$$q = I\eta\sigma n$$

- with $\eta I\sigma$ being probability per unit time of producing an ion pair (=ionization rate)
- σ - cross section for the absorption of radiation
- η – ionisation efficiency

Increment of optical depth τ

$$-\frac{dI}{I} = d\tau = \sigma n ds$$

$$I = I_{\infty} e^{-\tau}$$

So the optical depth is the distance on which the incident flux reduces by *1/e*

For horizontally stratified atmosphere: $ds = -\,dh\ \sec\chi\ \ (\chi - \text{zenith angle})$

$$-\frac{d(\ln I)}{dh} = \frac{d\tau}{dh} = -\,\sigma n \sec\chi$$

So the optical depth becomes $\tau(h,\chi) = \int_{h}^{\infty} \sigma n \sec\chi dh = \sigma n(h) H \sec\chi$

And production per unit volume $q(h,\chi) = I_{\infty} \eta \sigma n(h) e^{-\tau(h,\chi)}$

Chapman layer

The production rate is

$$q(z,\chi) = q_0 \exp[1 - z - e^{-z}\sec\chi]$$

with $q_0 = \frac{\eta I_\infty}{eH}$ for overhead sun.

Assuming recombination rate αN^2, we get

the production function

$$N(z) = (q_0/\alpha)^{1/2} \exp\tfrac{1}{2}(1 - z - e^{-z}\sec\chi)$$

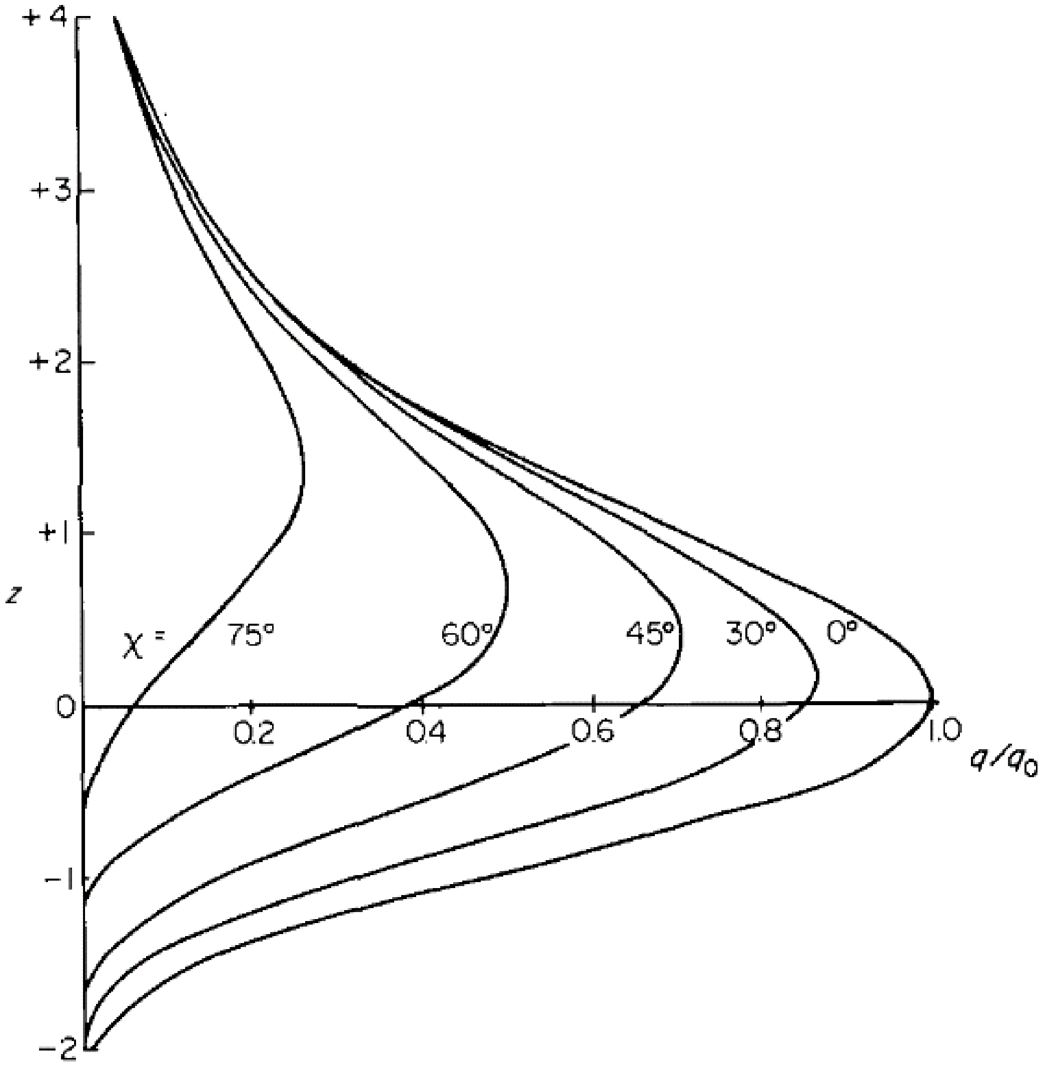
known as Chapman layer, or Chapman alpha

From here the critical frequency f_0 (in

Hz) relates to the peak concentration

N_m (in m^{-3})

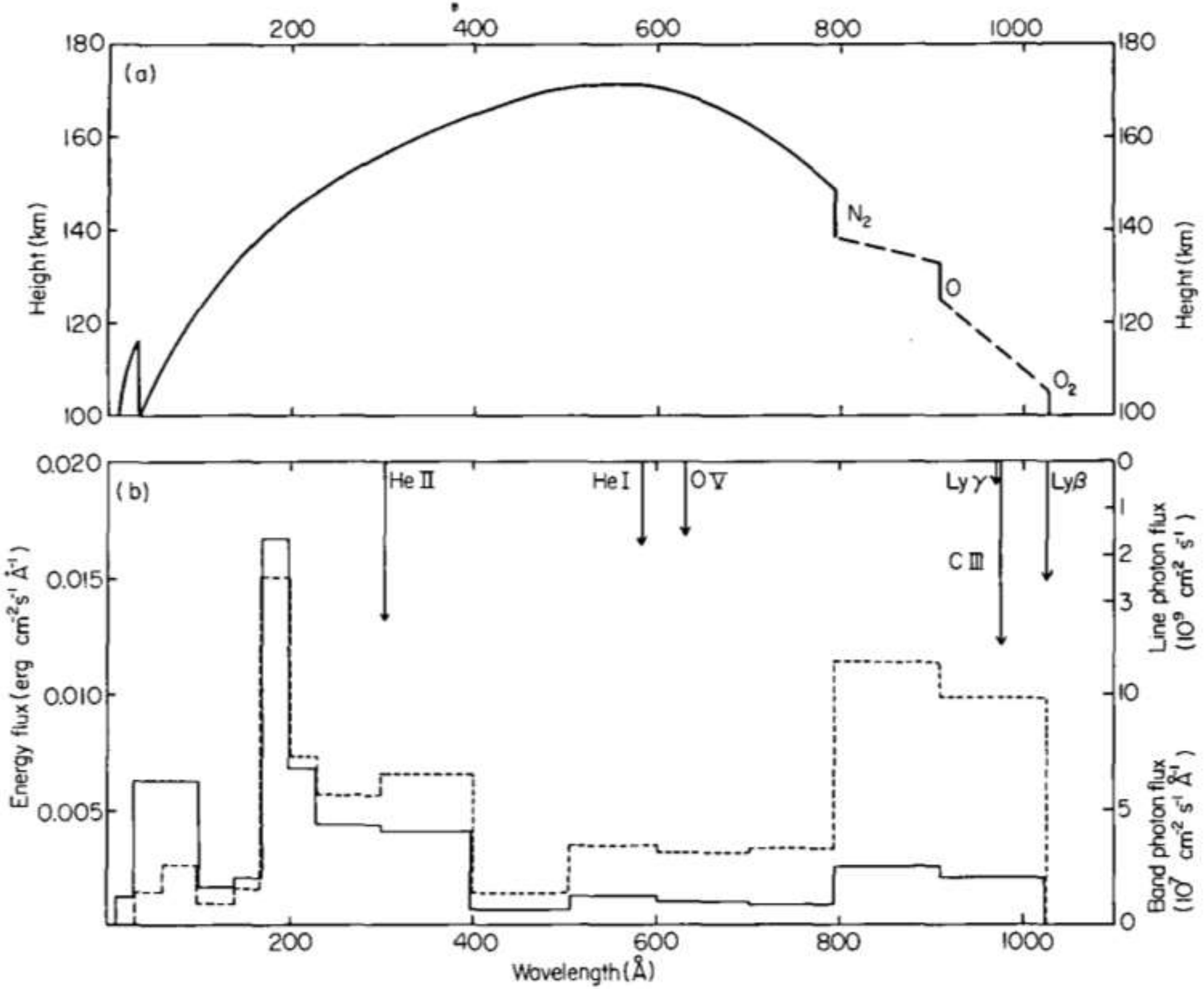
$$f_0 = 9\, N_m^{1/2} = 9(q_0/\alpha)^{1/4}(\cos\chi)^{1/4}$$



Production of ionospheric layers

Height of unit optical depth for vertically incident radiation, as a function of wavelength.

Solar flux for several wavelength bands. The area below the broken lines indicates photon flux; the area below the full lines indicates energy flux.



Production of F- and E-regions

F-region:

- 500-600 A range with unit optical depth at 170km, including the strong line emission He I (584 A), also He II (304 A) and O V (630 A).
- The long wavelength limit for F-region ionization is at ~796 A.

E-region:

- Production by X-rays band in the range 8-140 A and by 796-1027 A UV band.
- Relative importance of the X-ray and UV contributions may vary with the solar cycle.
- The photoelectrons produced by X-rays can produce secondary ionization, so the production is complex.

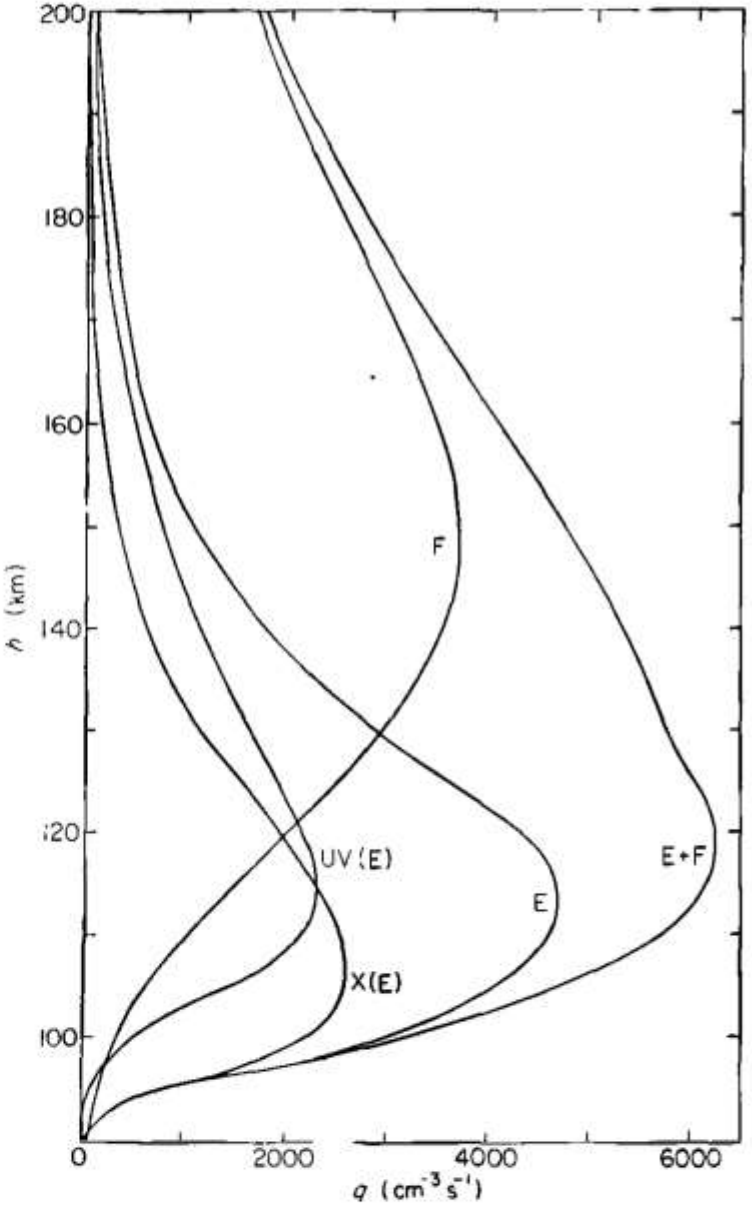


Fig. 24. Electron production profiles $q(h)$ for the E and F regions, for vertically incident radiation at sunspot number $R \simeq 60$. The curves refer to the following wavelength bands: X(E), 8–140 Å; UV(E) 796–1027 Å; E = UV(E) + X(E); F, 140–796 Å; E + F, total 8–1027 Å [after Allen (1965)]. [*Note:* 1 $cm^{-3}\,s^{-1} = 10^6\,m^{-3}\,s^{-1}$.]

Production of D-region

D-region:

- Lyman α (first spectral line of hydrogen).
- Cosmic rays from galactic sources.
- Energetic particles from the magnetosphere.
- Ionization sources vary strongly over solar cycle.

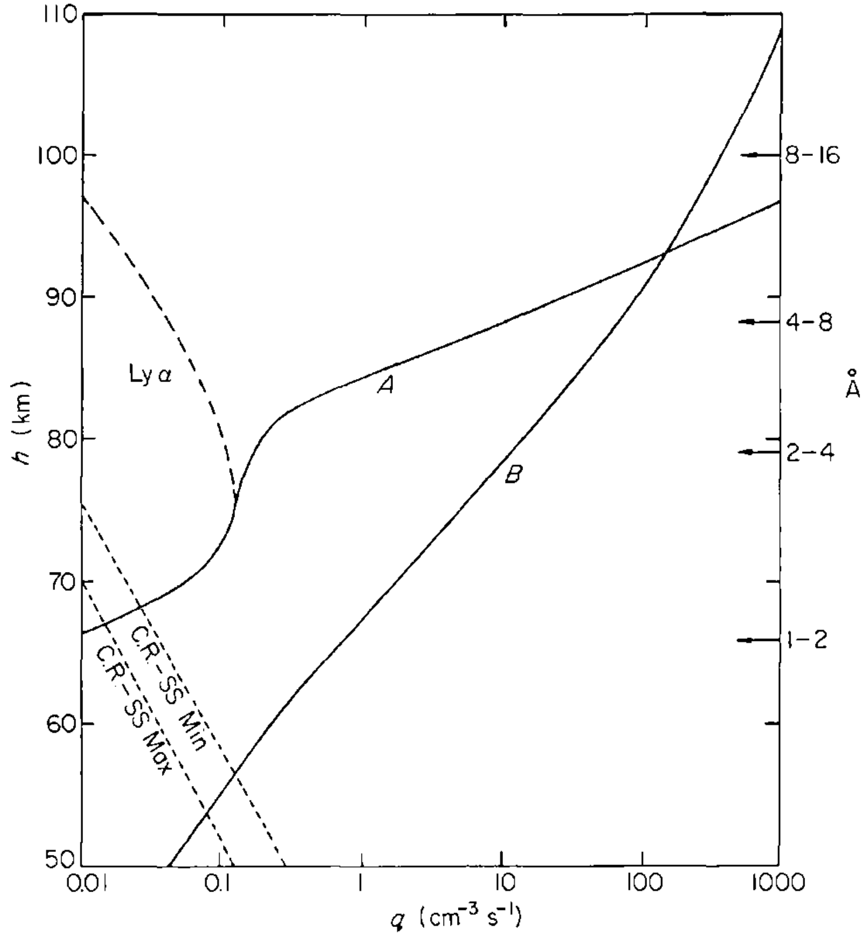


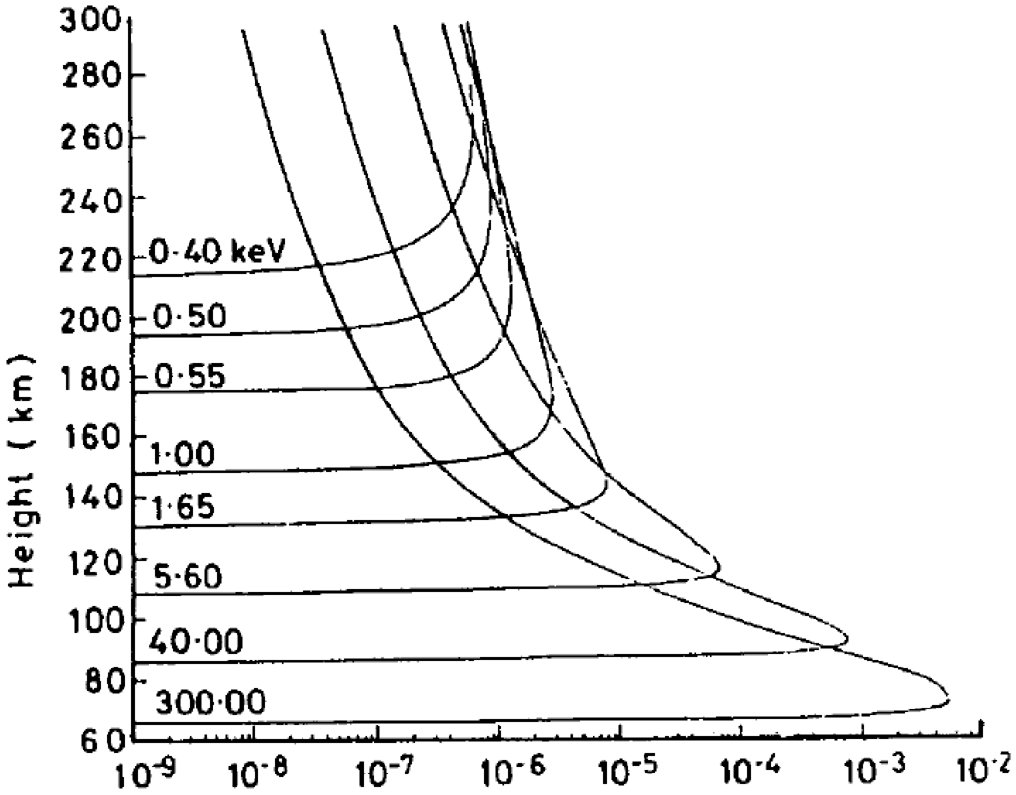
Fig. 25. Production profiles $q(h)$ for the D region, for vertically incident radiation. The arrows indicate the heights of peak production for four X-ray wavelength bands. Curve A represents quiet conditions at sunspot number $R \simeq 60$, the contribution of Lyman α being shown. Curve B represents the additional production due to a moderate solar flare (importance 2) [after Allen (1965)]. The dashed curves indicate production rates due to galactic cosmic rays, at magnetic latitude 50°, at sunspot minimum and maximum [after Webber (1962)].

Corpuscular (particle) ionization

Sources of energetic particles:

- Solar energetic proton events.
- Magnetospheric storms and substorms (mainly auroral electrons, 10s of keV).
- Earth's radiation belts (relativistic electrons,100s keVs- MeVs).

Ionization rates due to electron precipitations



Recombination mechanisms

Ion-ion recombination (coefficient α_i):

$X^+ + Y^- \rightarrow X + Y$

Mainly in D-region, otherwise not enough negative ions

Electron-ion recombination (coefficient α_e):

Three-body: $X^+ + e + M \rightarrow X + M$

Can take place in D-region, but higher up are unimportant

Radiative: $X^+ + e \rightarrow X^* \rightarrow X + hv$

Slow, could only become the fastest process in the upper F-region

Dissociative: $XY^+ + e \rightarrow X^* + Y^*$

Fastest recombination process in the E-region and the lower F-region

Formation of molecular ions and detachments

Large proportion of the ions in the E- and F-regions are atomic, so dissociative recombination must be preceded by reactions involving formation of molecular ions

Ion-atom interchange (rate coefficient *γ):*

$X^+ + YZ \rightarrow XY^+ + Z$

Thus primary loss in the E- and F-regions is ion-atom exchange followed by dissociative recombination.

Various detachment processes could be important

$X^- + M \rightarrow X + e + M$: collisional detachment (coefficient δ)

$X^- + Y \rightarrow XY + e$: associative detachment (usually included in δ)

$X^- + h\nu \rightarrow X + e$: photo detachment (coefficient ρ)

Process	Contribution to continuity equation (reactions/unit volume/unit time) and rough values of coefficients	D Region 50–90 km (approx.)	E Region 90–150 km (approx.)	F Region 150–600 km (approx.)
PRODUCTION			EUV 911–1027 Å	EUV 170–911 Å
Solar photoionization (principal radiations shown [ ])	$q(h)$	[Ly α 1216 Å] (ionizes NO) X-rays 1–10 Å	[Ly β 1026 Å] O_2 ionized by $\lambda < 1027$ Å X-rays 10–170 Å	[He II 304 Å, He I 584 Å] O ionized by $\lambda < 911$ Å N_2 ionized by $\lambda < 796$ Å
Corpuscular ionization (more important at high latitudes, especially auroral zone)	$q(h)$	Electrons > 30 keV Protons > 1 MeV Cosmic rays	Electrons 1–30 keV cause some nighttime and sporadic E ionization	Electrons $\lesssim$ 1 keV (probably small; might be significant at night)
LOSS				
Ion-ion recombination	$\alpha_i N_+ N_-$ $\alpha_i \sim 10^{-7}$ cm^3 s^{-1} = 10^{-13} m^3 s^{-1}	Important	Few negative ions exist	Very few negative ions exist
Electron-ion recombination	$\alpha_e N_+ N_e$			
Three-body recombination	$\alpha_e = \alpha(h)$	Important	Gas densities too low	Gas densities too low
Radiative recombination	$\alpha_e \sim 10^{-12}$ cm^3 s^{-1} = 10^{-18} m^3 s^{-1}	Insignificant	Not important	Not important
Dissociative recombination	$\alpha_e \sim 10^{-7}$ cm^3 s^{-1} = 10^{-13} m^3 s^{-1}	Important	Principal loss mechanism	Principal loss mechanism
Ion-atom interchange (N_{A^+} = atomic ion concentration)	$\beta(h) N_{A^+} \equiv \gamma n[M] N_{A^+}$ $\gamma \sim 10^{-11}$ cm^3 s^{-1} = 10^{-17} m^3 s^{-1}	Not important, because few atomic ions exist	Important	Important
Attachment	$a(h) N_e \equiv a_r n[X] N_e + a_t n[X] n[M] N_e$	Three-body attachment is most important	Can maintain some negative ions at night	Radiative attachment provides a very weak source of negative ions
Radiative	$a_r \sim 10^{-15}$ cm^3 s^{-1} = 10^{-21} m^3 s^{-1}			
Three-body	$a_t \sim 10^{-30}$ cm^6 s^{-1} = 10^{-42} m^6 s^{-1}			
Collisional detachment, etc.	$\delta(h) N_e \equiv \kappa n[M] N_-$	Important, especially at night	Fairly important	Insignificant
Collisional detachment	$\kappa \sim 10^{-20}$ cm^3 s^{-1} = 10^{-26} m^3 s^{-1}			
Associative detachment	$\kappa \sim 10^{-10}$ cm^3 s^{-1} = 10^{-16} m^3 s^{-1}			
Detachment by metastable molecules	$\kappa \sim 10^{-10}$ cm^3 s^{-1} = 10^{-16} m^3 s^{-1}			
Photodetachment by solar visible and long UV radiation	ρN_- $\rho \sim 1$ s^{-1}	Main cause of day/night change of N_-/N_e	Effective by day	Largely responsible for absence of negative ions

From Rishbeth and Garriott, 1969

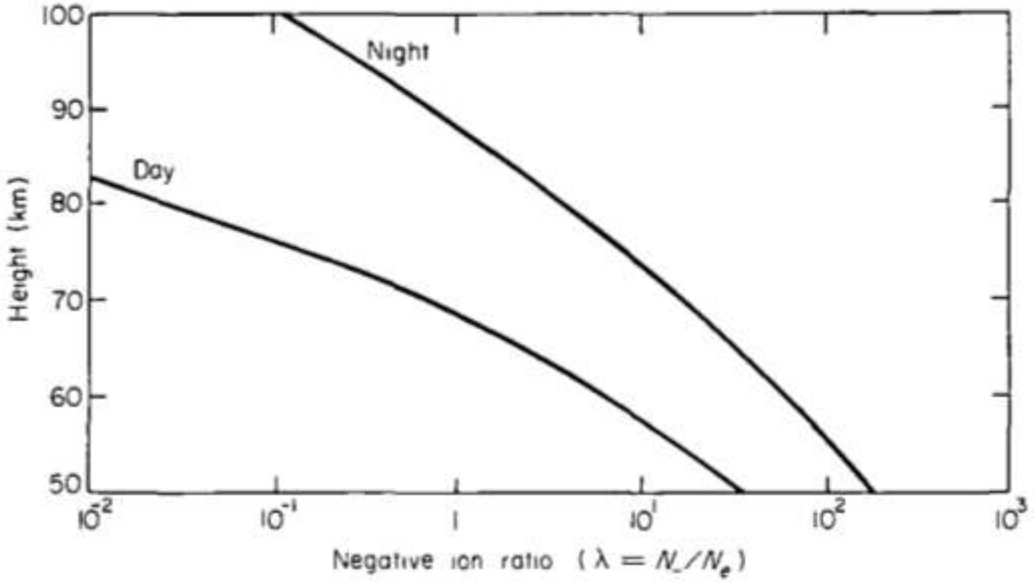
D-region balance

- Transport of ionization may be neglected in lower ionosphere.
- Only photochemical terms appear in the continuity equations.

Continuity equations

$$dN_+/dt = q - \alpha_e N_+ N_e - \alpha_i N_+ N_-$$
$$= q - (\alpha_e + \lambda\alpha_i) N_+ N_e$$
$$dN_e/dt = q - \alpha_e N_+ N_e - aN_e + (\rho + \delta) N_-$$
$$dN_-/dt = aN_e - (\rho + \delta) N_- - \alpha_i N_+ N_-$$

+ quasi-neutrality $N_+ = N_- + N_e = (1 + \lambda) N_e$



Balance equation

$$(1 + \lambda) dN_e/dt = q - (1 + \lambda)(\alpha_e + \lambda\alpha_i) N_e^{\,2}$$
$$= q - \alpha_E N_e^{\,2}$$

Effective recombination α_E approaches α_e with altitude

E- and F-region balance

Continuity equations for electrons, atomic ions and molecular ions
(γ is Ion-atom interchange rate and α is mainly dissociative recombination rate)

$$dN/dt = q - \alpha N N_{\mathrm{M}^+}$$
$$dN_{\mathrm{A}^+}/dt = q - \gamma n[\mathrm{M}]\, N_{\mathrm{A}^+}$$
$$dN_{\mathrm{M}^+}/dt = \gamma n[\mathrm{M}]\, N_{\mathrm{A}^+} - \alpha N N_{\mathrm{M}^+}$$

+ quasi-neutrality $N = N_{\mathrm{A}^+} + N_{\mathrm{M}^+}$

assume equilibrium conditions ($d/dt = 0$) and write $\beta = \gamma n[\mathrm{M}]$

$N_{\mathrm{A}^+}/N_{\mathrm{M}^+} = \alpha N/\beta$ → quadratic eqn for electron concentration: $\alpha\beta N^2 - \alpha q N - \beta q = 0$

Two limiting cases

$q = \alpha N^2$ if $\beta \gg \alpha N$, so that $N_{\mathrm{M}^+} \gg N_{\mathrm{A}^+}$ faster quadratic loss at lower altitudes

$q = \beta N$ if $\beta \ll \alpha N$, so that $N_{\mathrm{M}^+} \ll N_{\mathrm{A}^+}$ slow linear loss at higher altitudes since β depends on neutral concentration