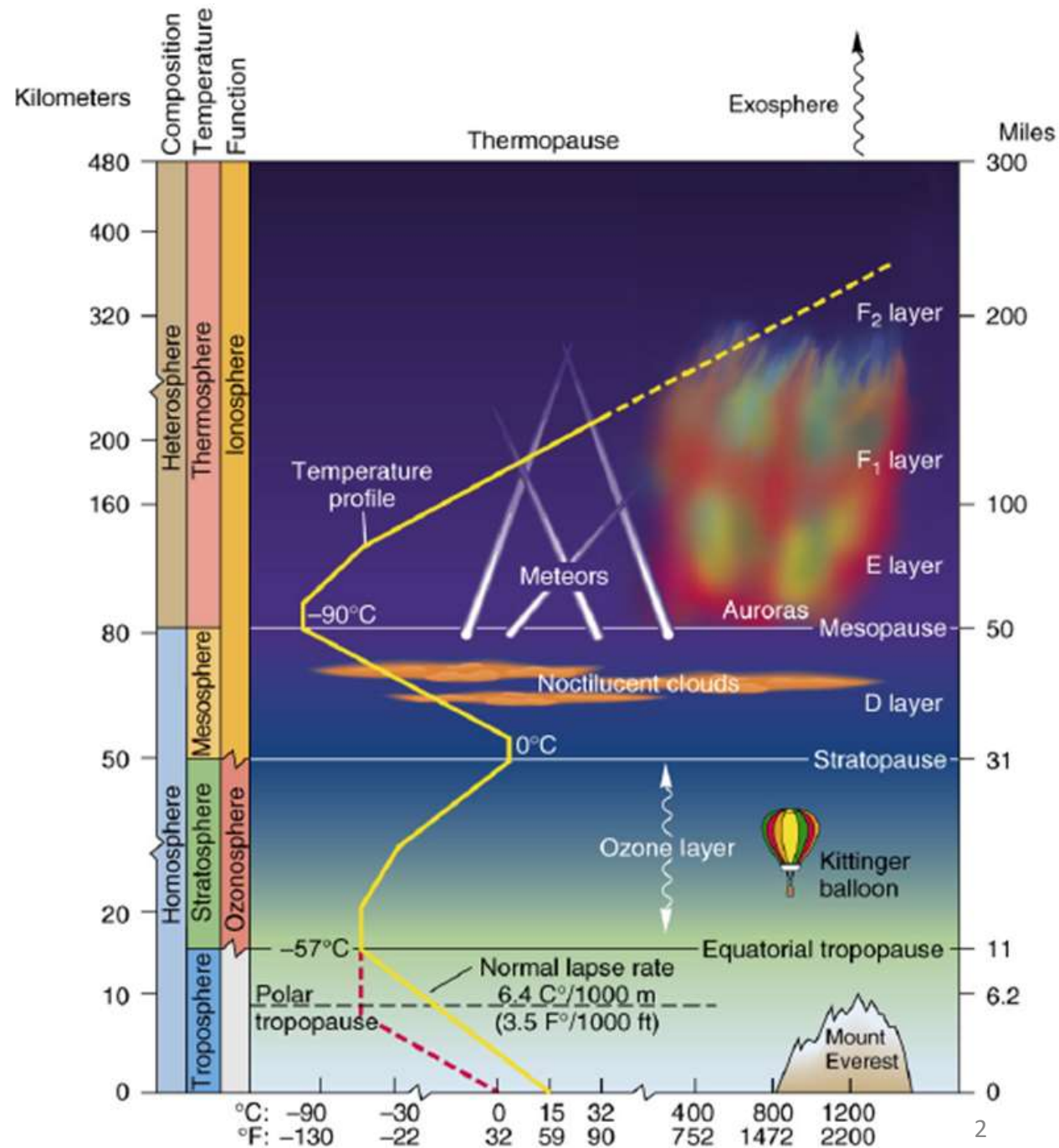
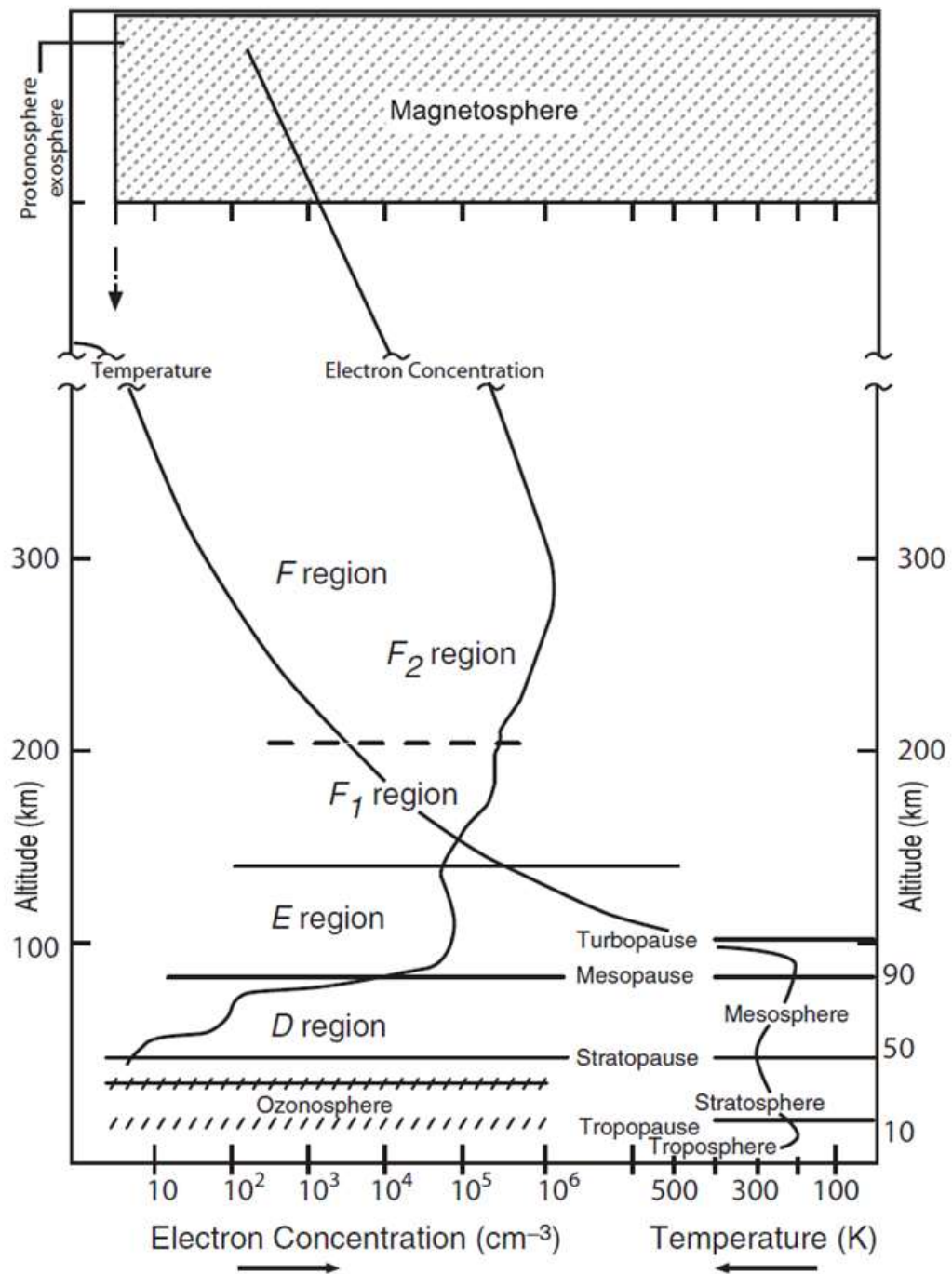


# Formation of the ionosphere: photochemical equilibrium

Additional reading:

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



## 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.

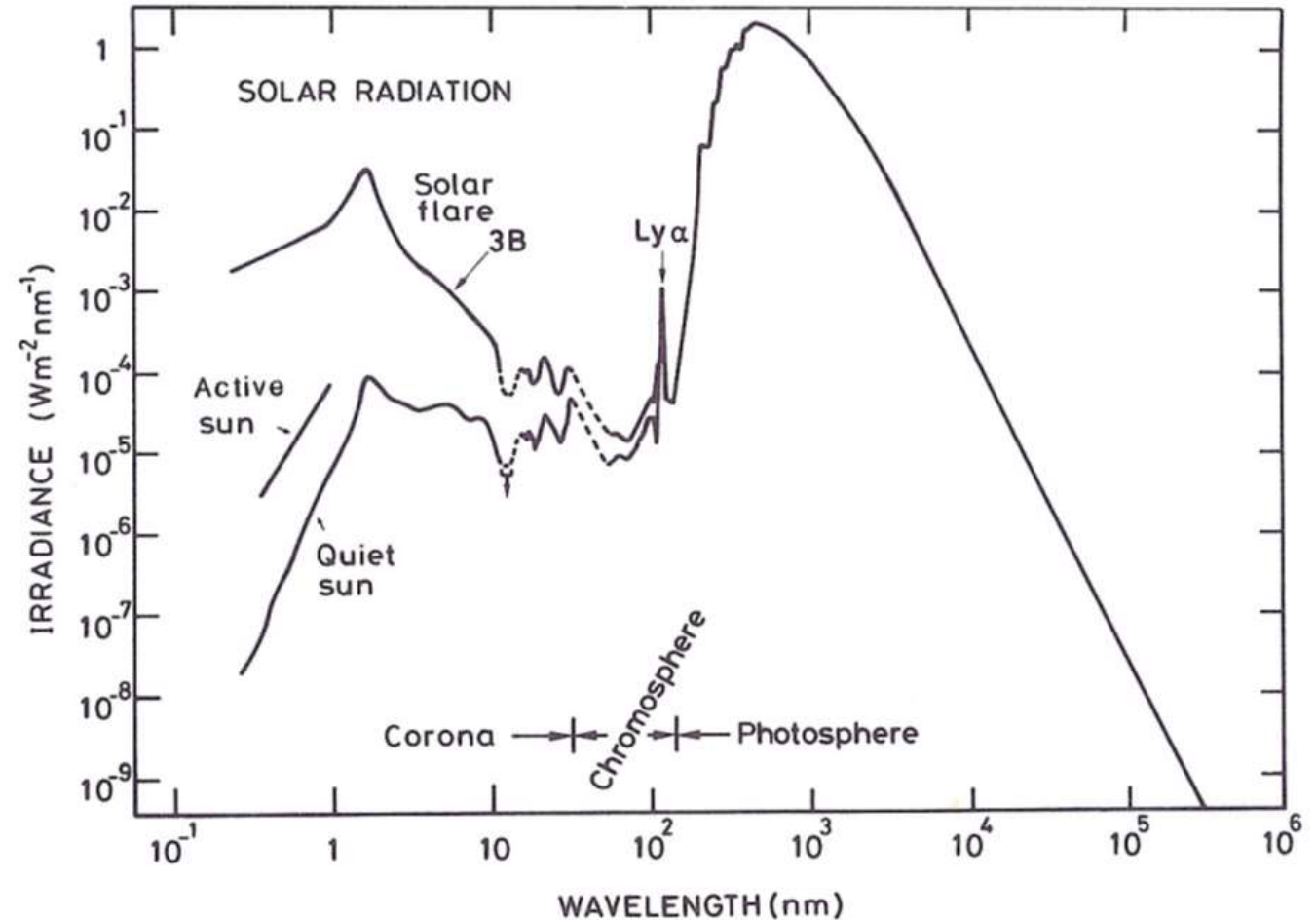
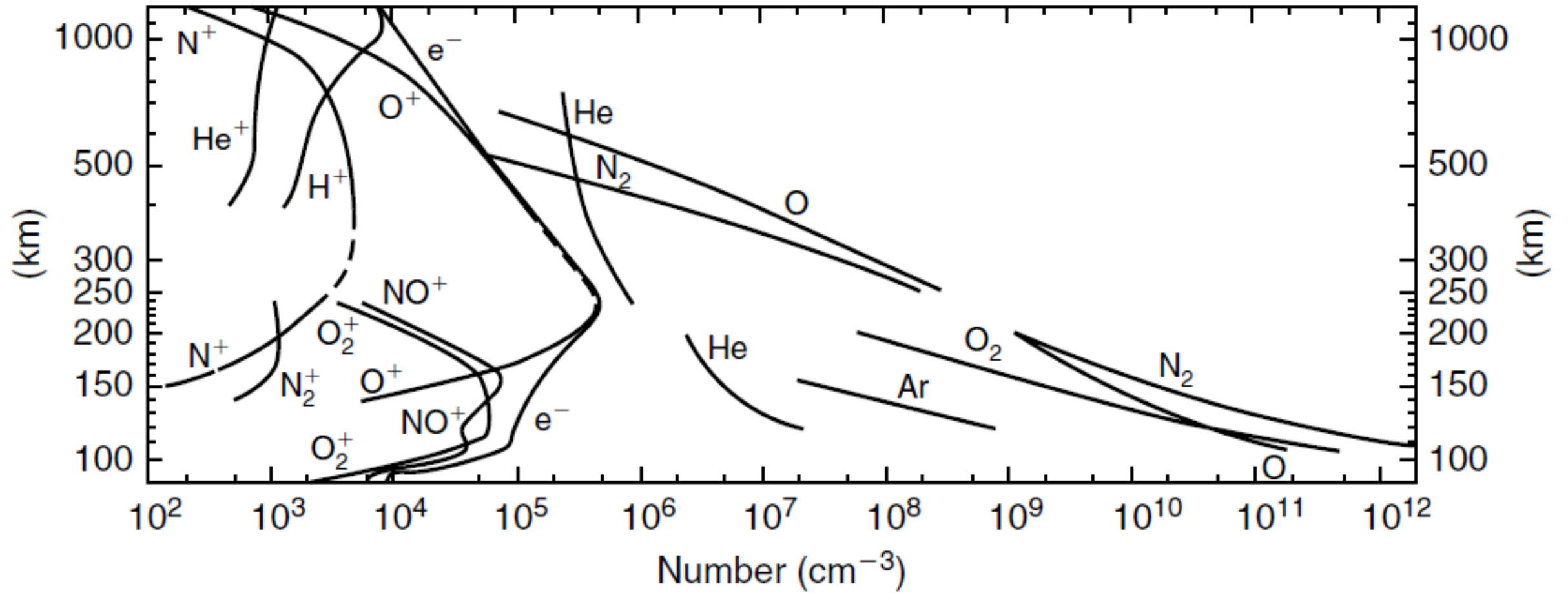


Fig. 4.5. Spectral distribution of the solar irradiance, and its variation with solar activity. The logarithmic representation emphasizes the contribution of x-rays and extreme ultraviolet radiation. After Smith and Gottlieb (1974).

# Neutral and ionized components



## Balance of ionization

$$\begin{array}{l} \text{Rate of change} \\ \text{of electron} \\ \text{concentration} \end{array} = \begin{array}{l} \text{Gain by} \\ \text{production} \end{array} - \begin{array}{l} \text{Loss by} \\ \text{destruction} \end{array} - \begin{array}{l} \text{Change due} \\ \text{to transport} \end{array}$$

## Continuity equation

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

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)
- $\sigma$  - cross section for the absorption of radiation
- $\eta$  – ionisation efficiency

Increment of optical depth  $\tau$

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

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

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

For horizontally stratified atmosphere:  $ds = -dh \sec \chi$  ( $\chi$  – 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  $\alpha N^2$ , we get the production function

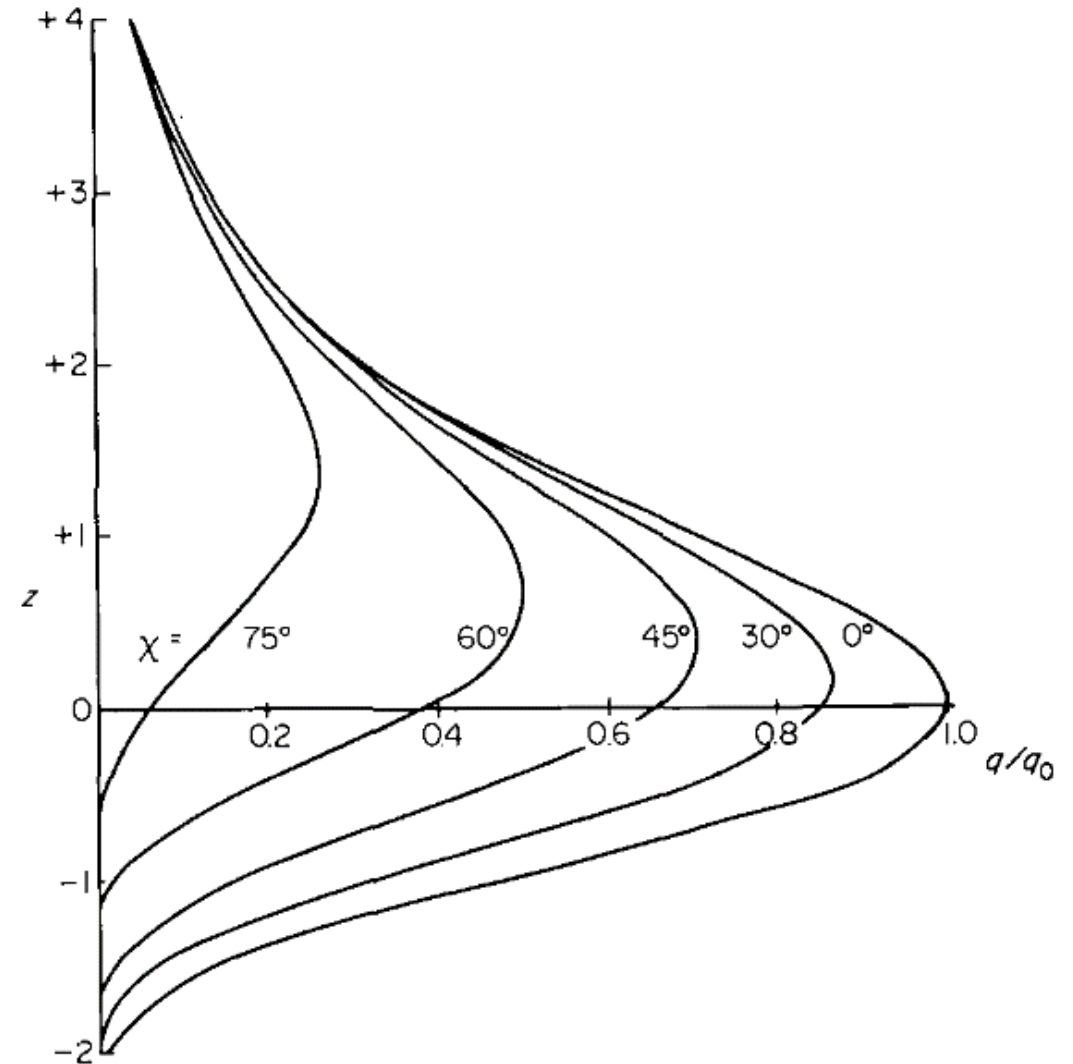
$$N(z) = (q_0/\alpha)^{1/2} \exp \frac{1}{2} (1 - z - e^{-z} \sec \chi)$$

known as Chapman layer, or Chapman alpha

From here the critical frequency  $f_0$  (in Hz) relates to the peak concentration

$N_m$  (in  $m^{-3}$ )

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

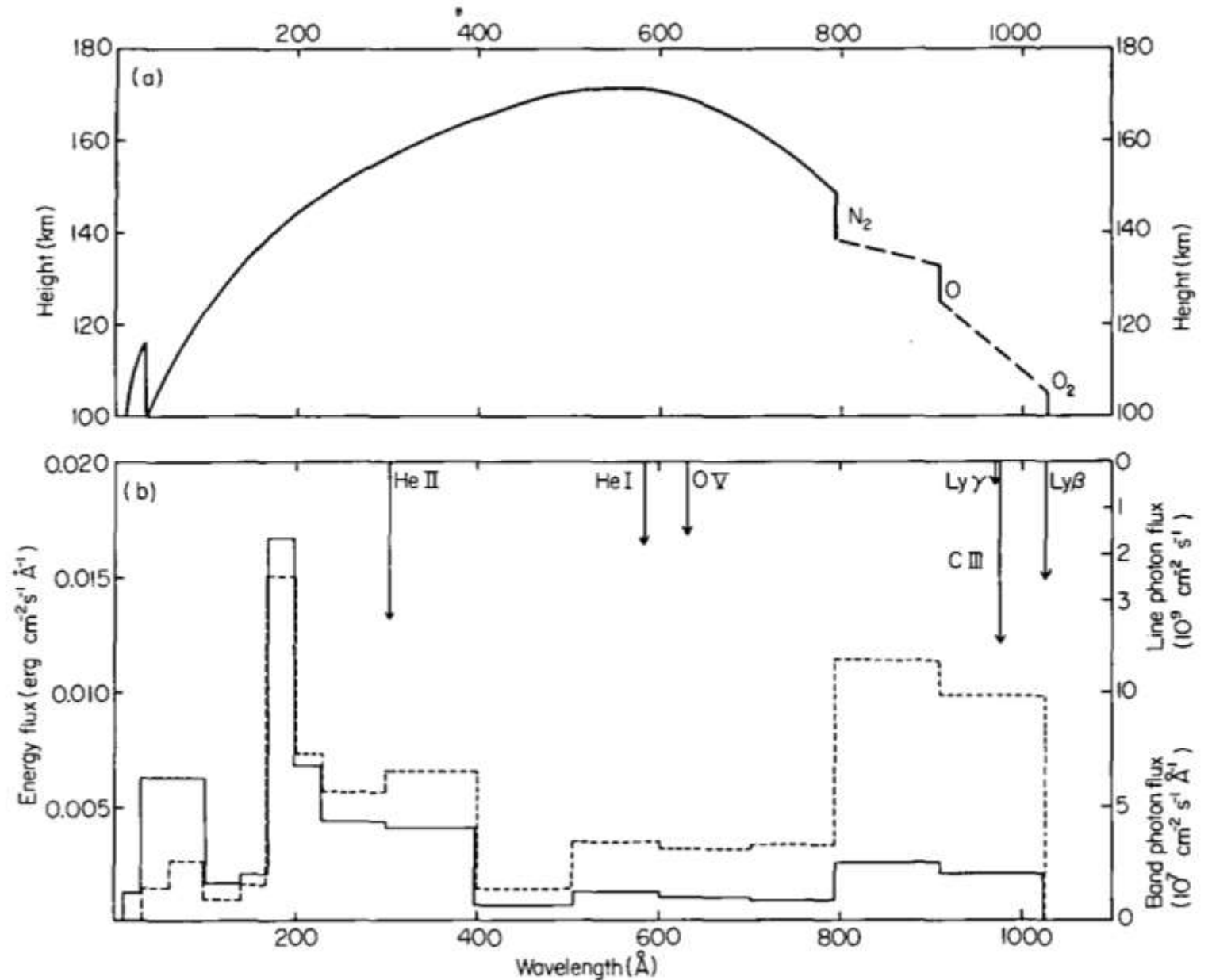




# Production of ionospheric layers

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.



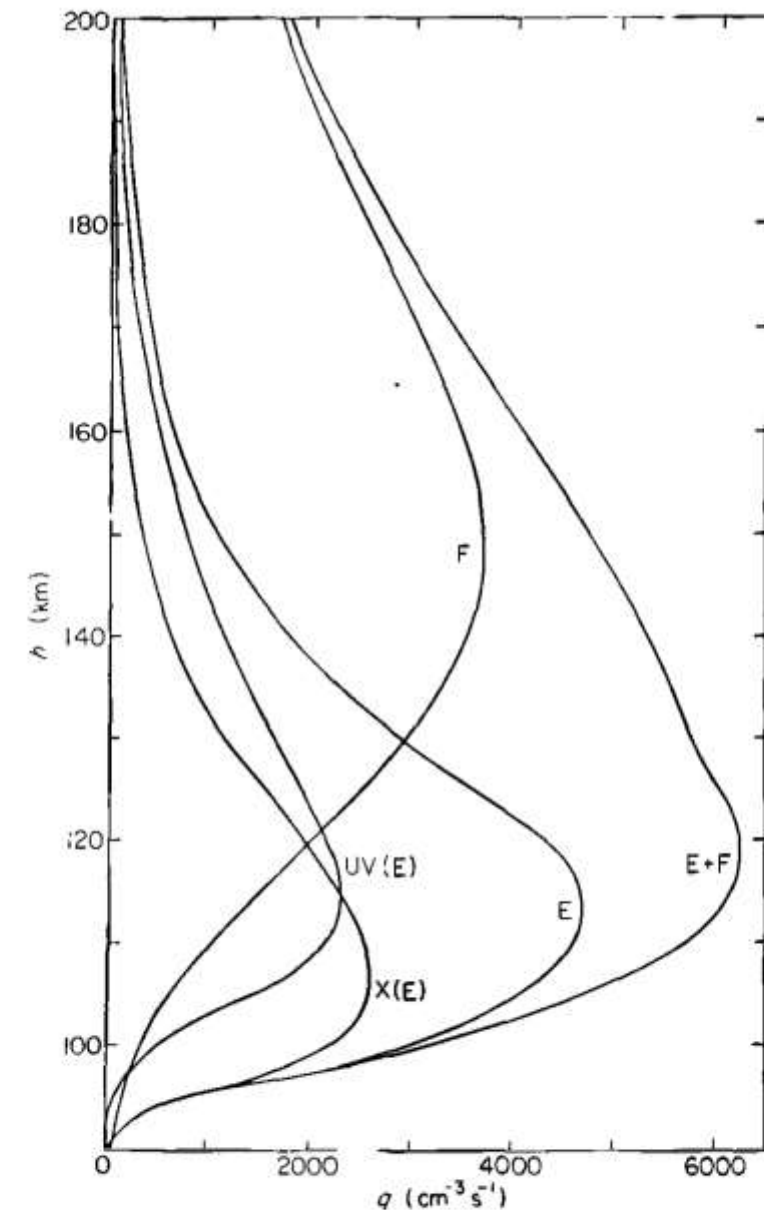
# Production of F- and E-regions

## F-region:

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

## E-region:

- Production by X-rays band in the range 8-140 Å and by 796-1027 Å 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.

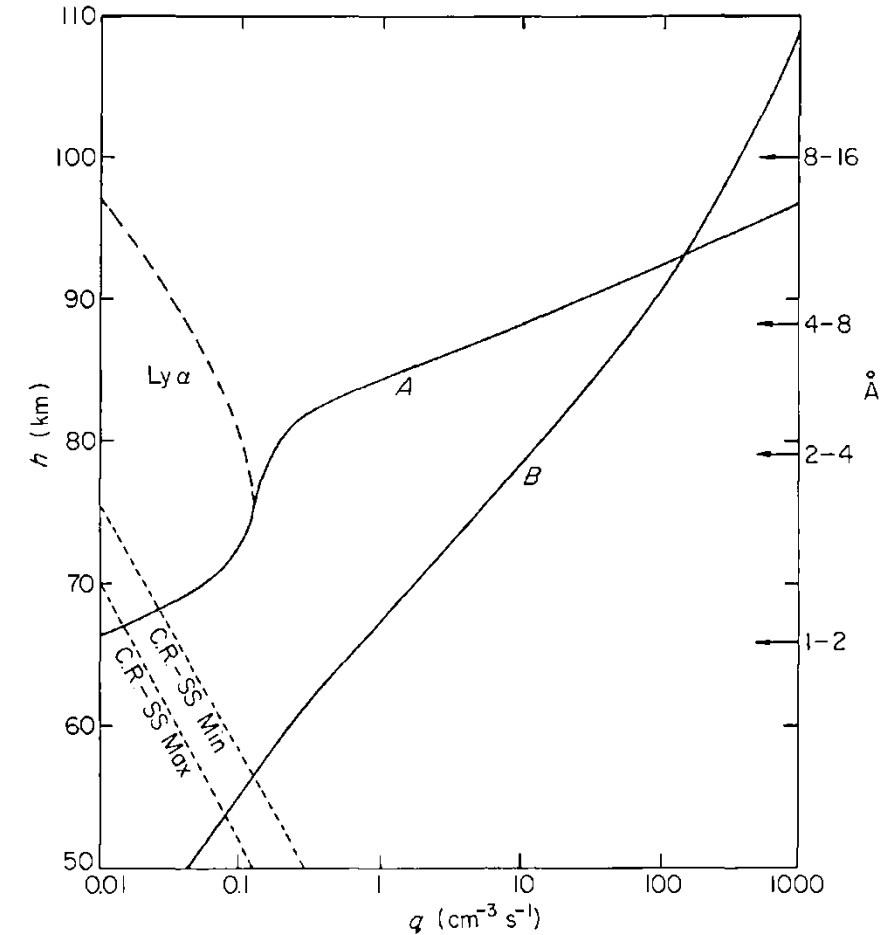


**Fig. 24.** Electron production profiles  $q(h)$  for the E and F regions, for vertically incident radiation at sunspot number  $R \approx 60$ . The curves refer to the following wavelength bands: X(E), 8–140 Å; UV(E) 796–1027 Å; E = UV(E) + X(E); F, 140–796 Å; E + F, total 8–1027 Å [after Allen (1965)].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

# Production of D-region

## D-region:

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



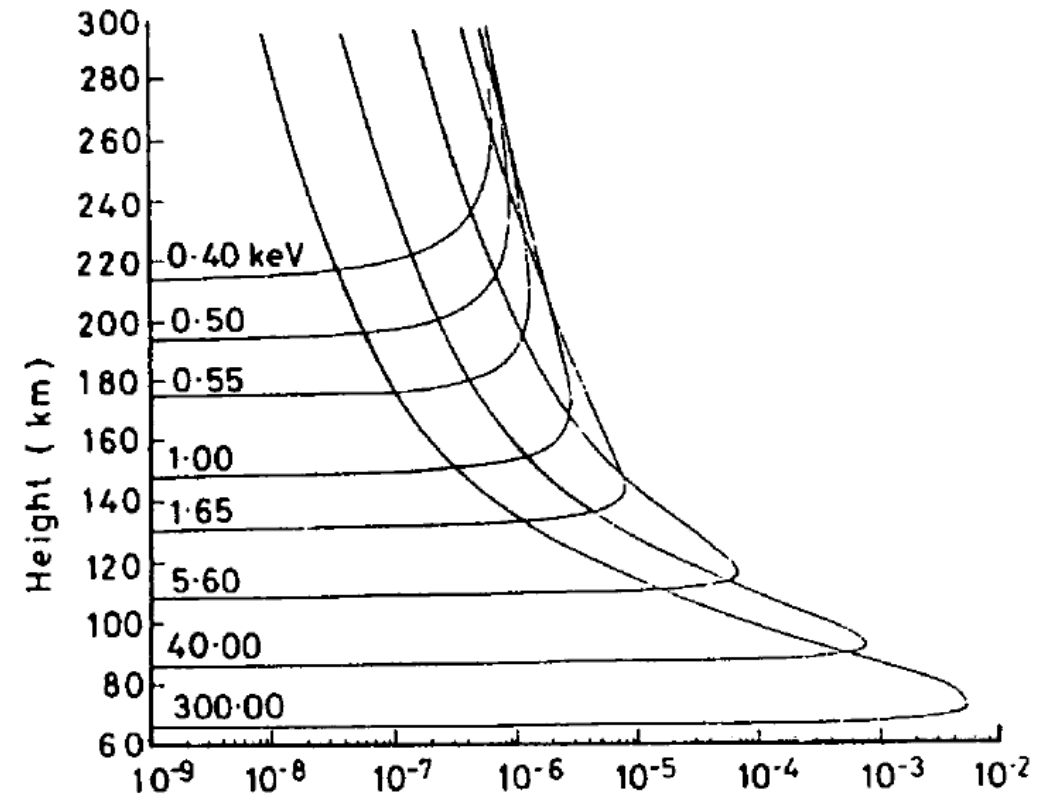
**Fig. 25.** Production profiles  $q(h)$  for the D region, for vertically incident radiation. The arrows indicate the heights of peak production for four X-ray wavelength bands. Curve *A* represents quiet conditions at sunspot number  $R \approx 60$ , the contribution of Lyman  $\alpha$  being shown. 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  $50^\circ$ , at sunspot minimum and maximum [after Webber (1962)].

# Corpuscular (particle) ionization

## Sources of energetic particles:

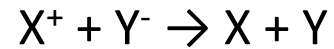
- Solar energetic proton events.
- Magnetospheric storms and substorms (mainly auroral electrons, 10s of keV).
- Earth's radiation belts (relativistic electrons, 100s keVs- MeVs).

Ionization rates due to electron precipitations



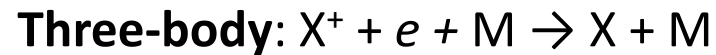
# Recombination mechanisms

**Ion-ion recombination** (coefficient  $\alpha_i$ ):

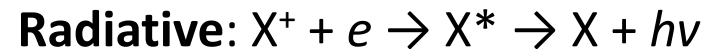


Mainly in D-region, otherwise not enough negative ions

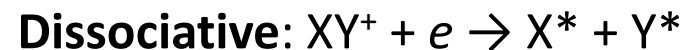
**Electron-ion recombination** (coefficient  $\alpha_e$ ):



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



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

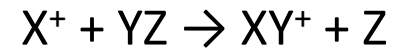


Fastest recombination process in the E-region and the lower F-region

# 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  $\gamma$ ):



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

**Various detachment processes could be important**



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.)
<b>PRODUCTION</b>				
<i>Solar photoionization</i> (principal radiations shown [ ])	$q(h)$	[Ly $\alpha$ 1216 Å] (ionizes NO) X-rays 1–10 Å	EUV 911–1027 Å [Ly $\beta$ 1026 Å] O <sub>2</sub> ionized by $\lambda < 1027$ Å X-rays 10–170 Å	EUV 170–911 Å [He II 304 Å, He I 584 Å] O ionized by $\lambda < 911$ Å N <sub>2</sub> ionized by $\lambda < 796$ Å
<i>Corpuscular ionization</i> (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 signifi- cant at night)
<b>LOSS</b>				
<i>Ion-ion recombination</i>	$\alpha_i N_+ N_-$ $\alpha_i \sim 10^{-7} \text{ cm}^3 \text{ s}^{-1} = 10^{-13} \text{ m}^3 \text{ s}^{-1}$	Important	Few negative ions exist	Very few negative ions exist
<i>Electron-ion recombination</i>	$\alpha_e N_+ N_e$			
Three-body recombination	$\alpha_e \rightarrow \alpha(h)$	Important	Gas densities too low	Gas densities too low
Radiative recombination	$\alpha_e \sim 10^{-12} \text{ cm}^3 \text{ s}^{-1} = 10^{-18} \text{ m}^3 \text{ s}^{-1}$	Insignificant	Not important	Not important
Dissociative recombination	$\alpha_e \sim 10^{-7} \text{ cm}^3 \text{ s}^{-1} = 10^{-13} \text{ m}^3 \text{ s}^{-1}$	Important	Principal loss mechanism	Principal loss mechanism
<i>Ion-atom interchange</i> ( $N_A^+$ = atomic ion con- centration)	$\beta(h) N_A^+ \equiv \gamma n[M] N_A^+$ $\gamma \sim 10^{-11} \text{ cm}^3 \text{ s}^{-1} = 10^{-17} \text{ m}^3 \text{ s}^{-1}$	Not important, be- cause few atomic ions exist	Important	Important
<i>Attachment</i>	$a(h) N_e \equiv a_r n[X] N_e$ $+ a_i n[X] n[M] N_e$	Three-body attach- ment is most im- portant	Can maintain some negative ions at night	Radiative attachment pro- vides a very weak source of negative ions
Radiative	$a_r \sim 10^{-15} \text{ cm}^3 \text{ s}^{-1} = 10^{-21} \text{ m}^3 \text{ s}^{-1}$			
Three-body	$a_i \sim 10^{-30} \text{ cm}^6 \text{ s}^{-1} = 10^{-42} \text{ m}^6 \text{ s}^{-1}$			
<i>Collisional detachment, etc.</i>	$\delta(h) N_e \equiv \kappa n[M] N_-$	Important, especially at night	Fairly important	Insignificant
Collisional detachment	$\kappa \sim 10^{-20} \text{ cm}^3 \text{ s}^{-1} = 10^{-26} \text{ m}^3 \text{ s}^{-1}$			
Associative detachment	$\kappa \sim 10^{-10} \text{ cm}^3 \text{ s}^{-1} = 10^{-16} \text{ m}^3 \text{ s}^{-1}$			
Detachment by metastable molecules	$\kappa \sim 10^{-10} \text{ cm}^3 \text{ s}^{-1} = 10^{-16} \text{ m}^3 \text{ s}^{-1}$			
<i>Photodetachment by solar visible and long UV radiation</i>	$\rho N_-$ $\rho \sim 1 \text{ s}^{-1}$	Main cause of day/ night change of $N_-/N_e$	Effective by day	Largely responsible for absence of negative ions

## D-region balance

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

Continuity equations

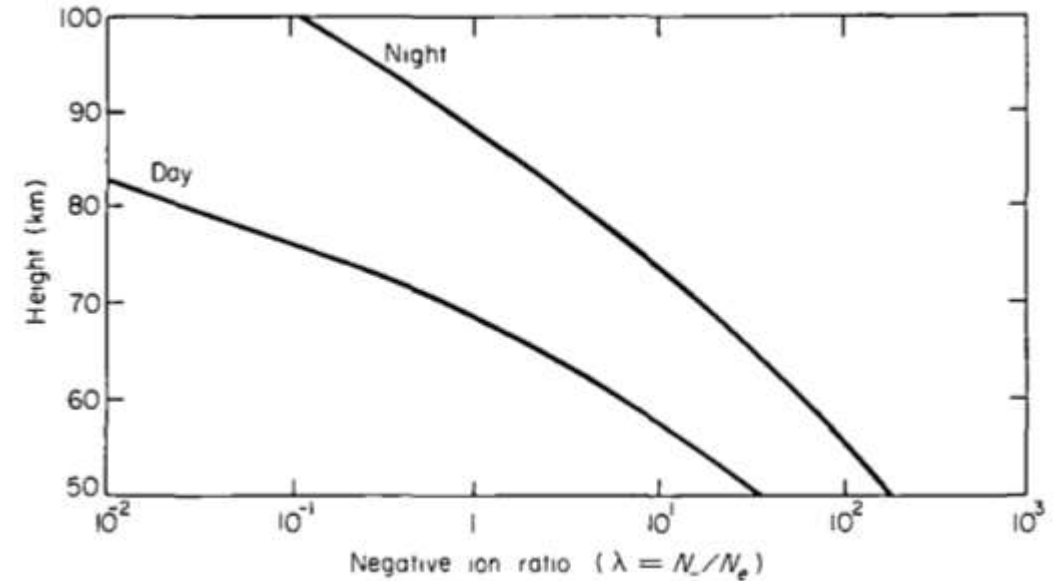
$$dN_+/dt = q - \alpha_e N_+ N_e - \alpha_i N_+ N_-$$

$$= q - (\alpha_e + \lambda \alpha_i) N_+ N_e$$

$$dN_e/dt = q - \alpha_e N_+ N_e - a N_e + (\rho + \delta) N_-$$

$$dN_-/dt = a N_e - (\rho + \delta) N_- - \alpha_i N_+ N_-$$

+ 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  $\alpha_E$   
approaches  $\alpha_e$  with altitude



# E- and F-region balance

## Continuity equations for electrons, atomic ions and molecular ions

( $\gamma$  is ion-atom interchange rate and  $\alpha$  is mainly dissociative recombination rate)

$$dN/dt = q - \alpha N N_{M+}$$

$$dN_{A+}/dt = q - \gamma n [M] N_{A+}$$

$$dN_{M+}/dt = \gamma n [M] N_{A+} - \alpha N N_{M+}$$

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

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

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

Two limiting cases

$$q = \alpha N^2 \quad \text{if } \beta \gg \alpha N, \quad \text{so that } N_{M+} \gg N_{A+}$$

$$q = \beta N \quad \text{if } \beta \ll \alpha N, \quad \text{so that } N_{M+} \ll N_{A+}$$

faster quadratic loss at lower altitudes

slow linear loss at higher altitudes since  
 $\beta$  depends on neutral concentration