united nations
educational, scientific
and cultural
organization

international atomic
energy agency

the
abdus salam
international centre for theoretical physics

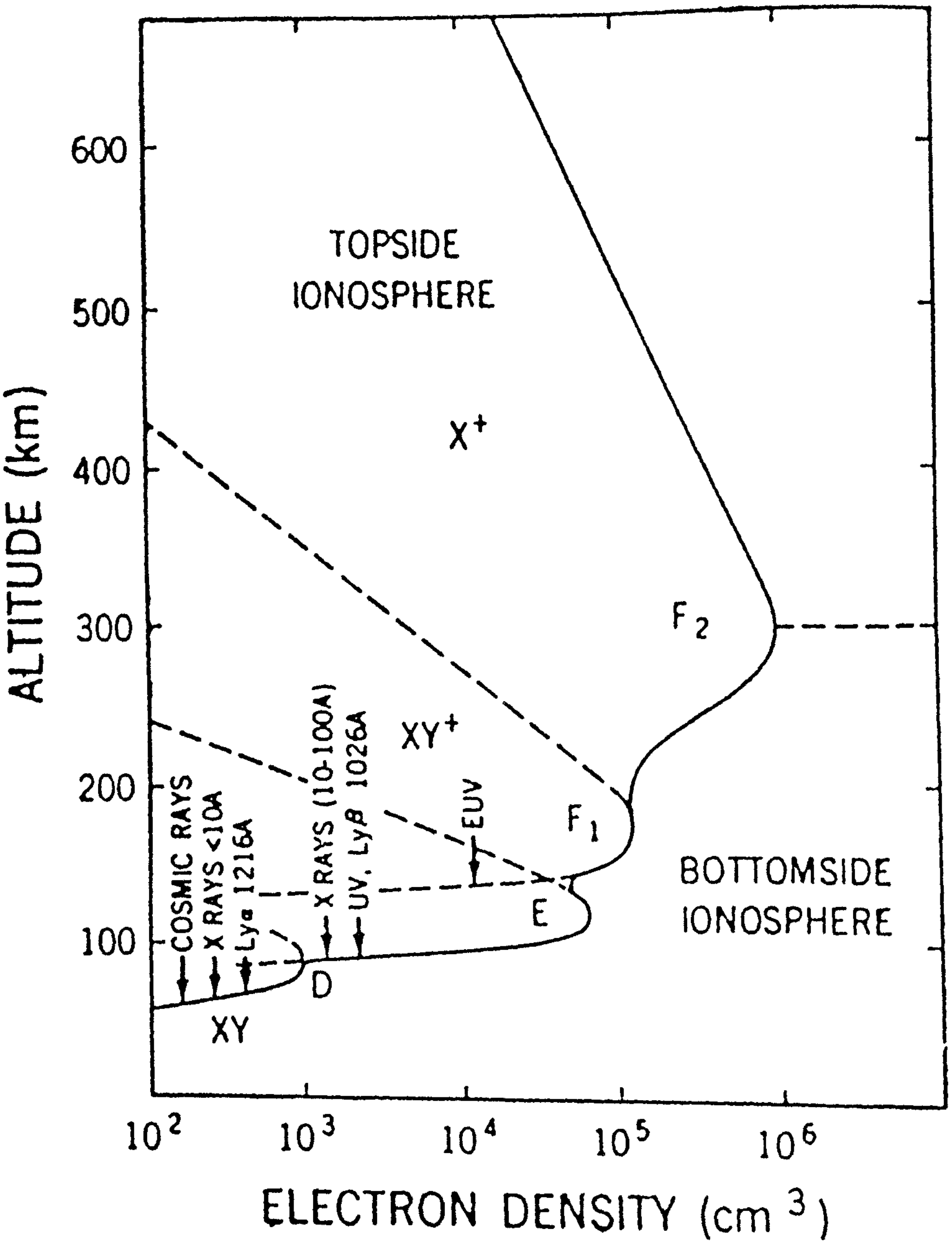
SMR/1328/24

School on the Physics of Equatorial Atmosphere

(24 September - 5 October 2001)

Basic Principles on the Formation of the Ionosphere

R. Sridharan
(Vikram Sarabhai Space Center, Trivandrum)


ALTITUDE (km)
600
500
400
300
200
100
TOPSIDE IONOSPHERE
X⁺
F 2
XY⁺
F 1
E
D
XY
BOTTOMSIDE IONOSPHERE
COSMIC RAYS
X RAYS <10A
Lyα 1216A
X RAYS (10-100A)
UV, Lyβ 1026A
EUV
10²
10³
10⁴
10⁵
10⁶
ELECTRON DENSITY (cm 3)

In general, the rate of change of electron density is expressed by means of a 'continuity equation'.

$$\frac{\partial N}{\partial t} = q - L - \mathrm{div}\,(NV) \tag{1}$$

Where 'q' is the production rate,

'L' is the loss rate and

div **(NV) Stands for the loss due to the transport, 'V' being the mean drift Velocity**

In order to really understand the Ionospheric formation, one has to go into the details of these processes.

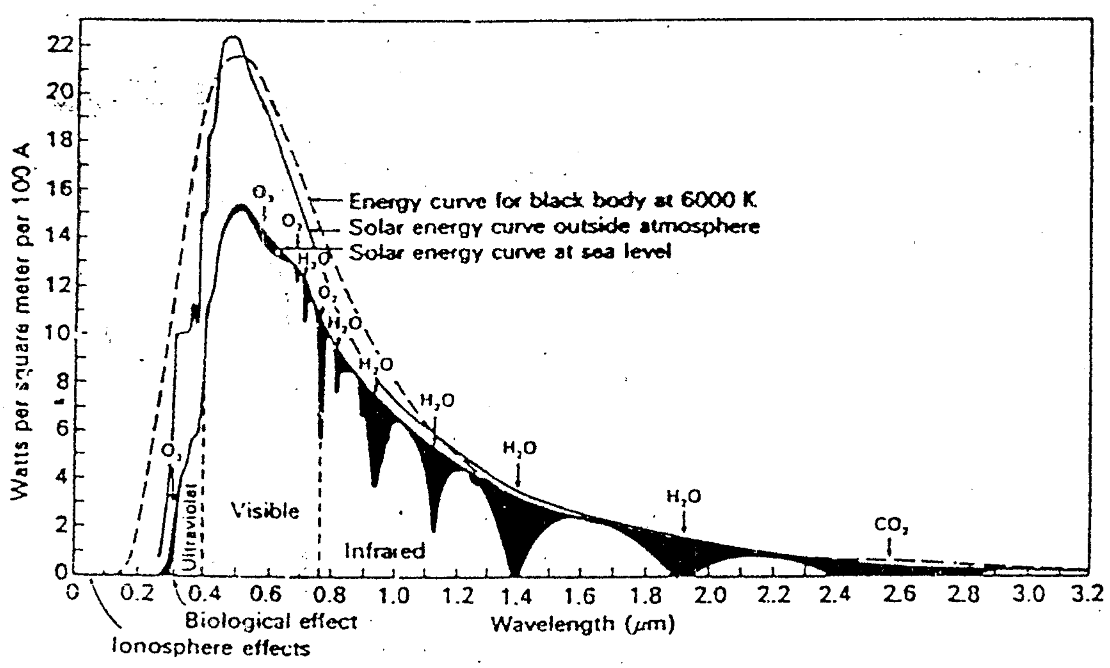


Fig. : The spectrum of solar electromagnetic radiation reaching the Earth's surface (including the effects of major absorbing species), and outside the atmosphere. The 6000 K black body curve is shown for comparison. The principal ionospheric effects are below 0.1 μm (100 nm). (After J. C. Brandt and P. W. Hodge, *Solar System Astrophysics*. McGraw-Hill, 1964)

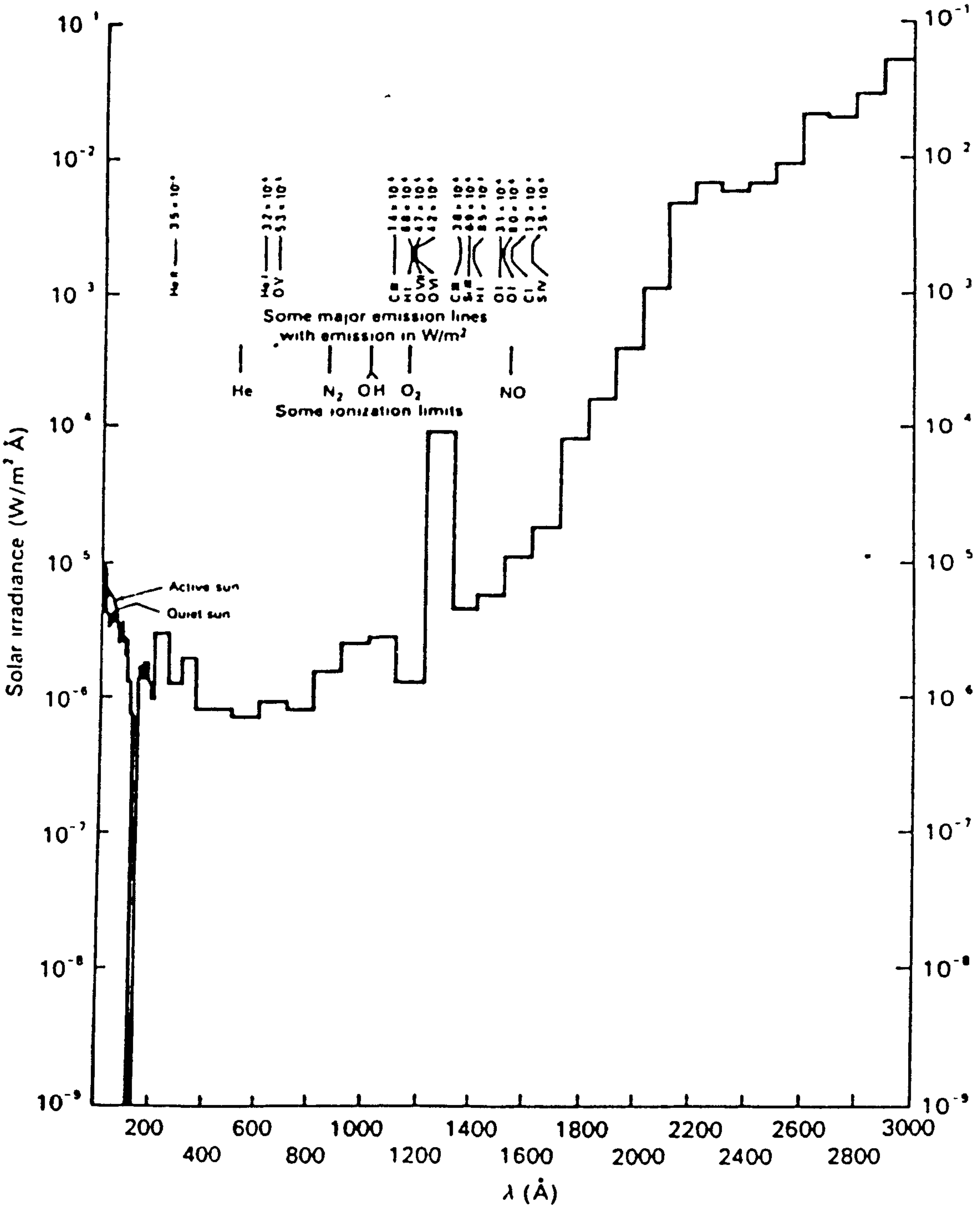


Fig. 6.9 Solar spectrum in the X-ray and UV regions (Data from E. V. P. Smith and D. M. Gottlieb, *Space Sci.Rev.* 16, 77, 1974 By permission of Kluwer Academic Publishers)

Table

Dissociation energy and first ionization potentials in ev and their corresponding wavelength

Constituent	*Dissociation energy (ev)*	λ_d(Å)	*Ionization potential* (*ev*)	λ_i(Å)	*Molecular diameter* (Å)
N_2	9.76	1373	15.58	796	0.5
O_2	5.11	2617	12.08	1026	3.2
NO	6.51	2058	9.25	1340	3.4
H_2	4·48	2990	15.41	804	2.5
N_2^+	8.73	1535	—	—	3.5
O_2^+	6.66	2010	—	—	3.2
NO^+	10.88	1230	—	—	3.4
H_2^+	2.65	5056	—	—	2.5
C	—	—	11.3	1100	—
O	—	—	13.61	911	—
H	—	—	13.59	912	—
N	—	—	14.55	922	—
A	—	—	15.75	787	—
Ne	—	—	21.56	575	—
He	—	—	24.58	504	—
H_2O	1.23	10000	12.6	985	3.5
N_2O	?	?	12.9	925	4.0
NH_3	?	?	10.15	122	3.0
CH_4	?	?	13.0	954	3.5
CO_2	8.0	1670	13.8	895	3.8
CO	11·1	1207	14.0	885	3.3
OH	4.4	3045	13.36	1000	—

The plus sign in N_2^+ or O^+ indicates a positive ion and shows that a single electron is removed from the parent molecule or atom indicating ionization of N_2 or O. In the

Typical reactions are

$$O_2 + h\nu\ (<2600A) \quad - \quad O(^3p) + O(^3p) \qquad (3)$$

$$O_2 + h\nu\ (<1750A) \quad - \quad O(^3p) + O(^1D) \qquad (4)$$

$$CO_2 + h\nu\ (<1670A) \quad - \quad CO + O(^1D) \qquad (5)$$

$$H_2O + h\nu\ (<1\mu) \quad - \quad OH + H \qquad (6)$$

Table 2

Constituent	Ionization potential eV	λ(A)
Na	5.14	2410
Ca	6.11	2028
Mg	7.64	1622
Fe	7.87	1575
Si	8.15	1570

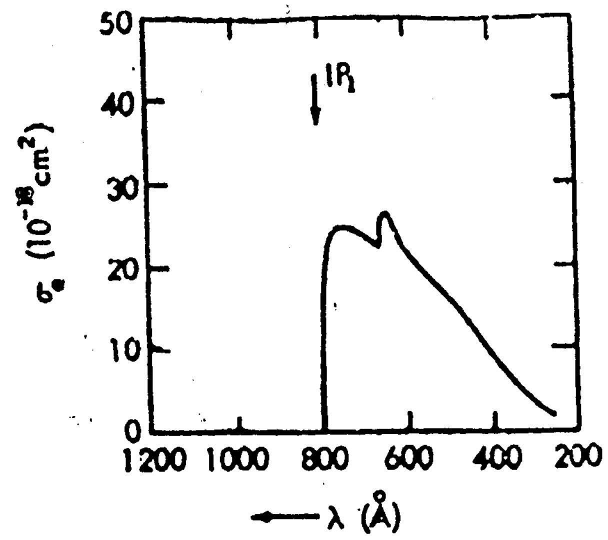


Fig. 4.2

Absorption cross-section of N_2 versus wavelength in Å (from McDaniel, 1964).

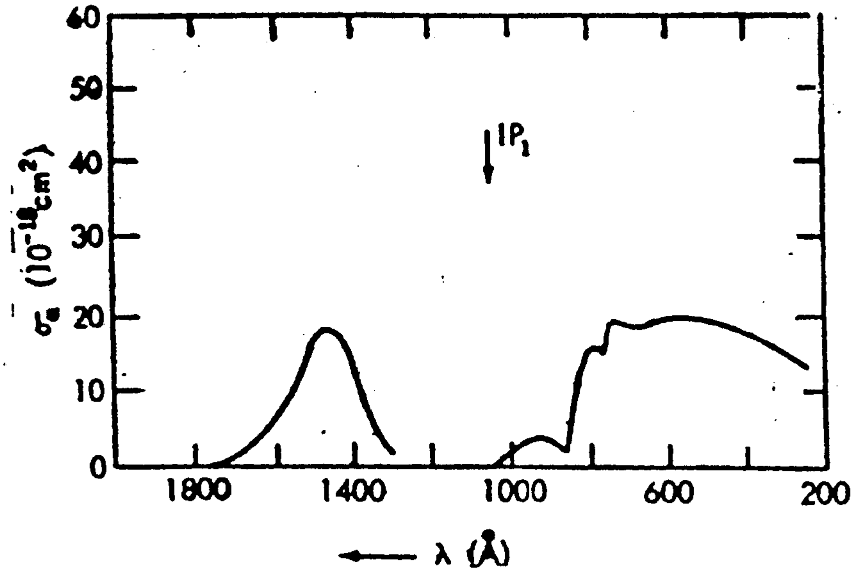
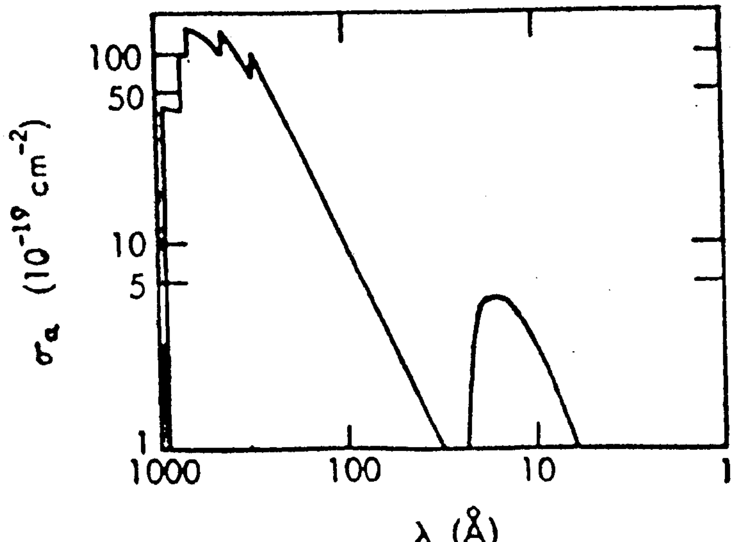


Fig. 4.3

Absorption cross-section of O_2 versus wavelength in Å from theoretical calculations (from McDaniel, 1964).

Fig. 4.4

Absorption cross-section of O versus wavelength in Å from theoretical calculations (from McDaniel, 1964).



If there are `n’ absorbing atoms per unit volume, each with an absorption coefficient σ_a, the intensity of the radiation varies with distance X’ as

$$\frac{dI}{dX} = \sigma_a \, n \, I \tag{7}$$

The intensity at that level could now be written as,

$$\frac{dI}{I} = \sigma_a \quad n \, dx \tag{8}$$

Integrating

$$\ln I = \sigma_a \, n \int_h^\infty d\,x \tag{9}$$

Considering a vertical column.

$$dx = dh \sec\chi \tag{10}$$

Where χ is the zenith angle.

$$\ln I = \sigma_a \, n \int_h^\infty dh \sec\chi \tag{11}$$

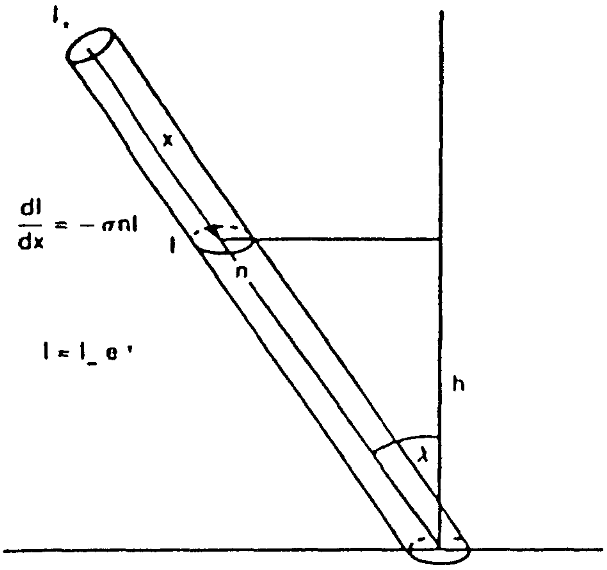
$$\ln I = \sigma_a \, n \, H \sec\chi \tag{12}$$

By defining a term ‘optical depth’ τ as the absorption coefficient time the number of absorbing atoms in a unit column down to the level being considered (σN_T), τ becomes

$$\tau = \sigma_a \, n \, H \, Sec \, \chi \tag{13}$$

$$\ln I = \tau \tag{14}$$

The intensity at any level `h’ is given as



Absorption of ionizing radiation in the atmosphere

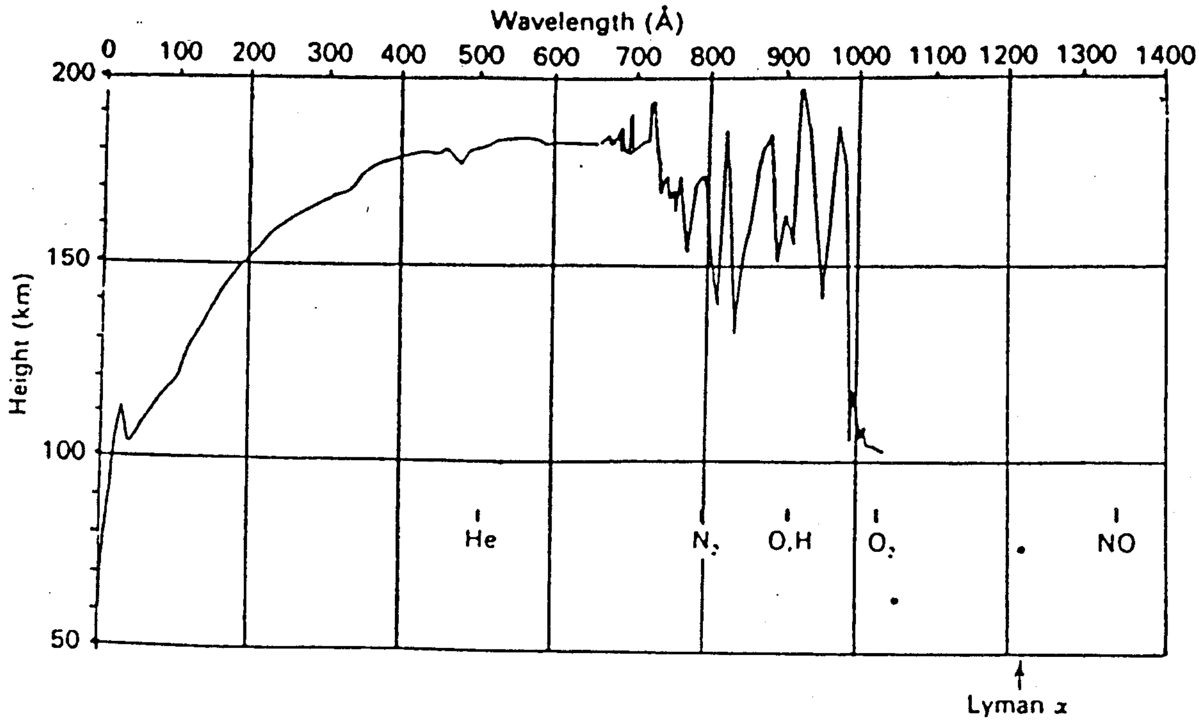
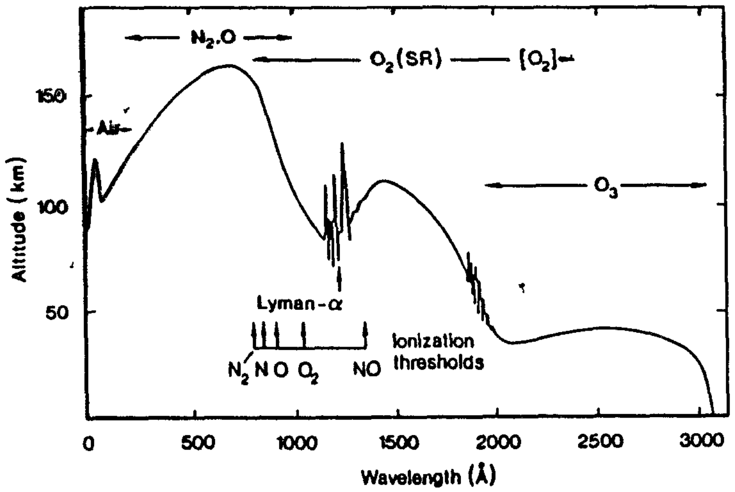


Fig. Height where the optical depth reaches unity for radiation vertically incident on a model atmosphere. Ionization limits for common gases are marked. The wavelength range is that involved in producing the ionosphere. (J. D. Mathews, private communication)



Altitude at which the solar irradiance decreases to e^{-1} of its value outside the Earth's atmosphere for vertical incidence The principal absorbing species are identified In the wavelength region labelled 'air' all constituents contribute to attenuation Wavelengths corresponding to the ionization thresholds of important species are marked by arrows (Adapted from L Herzberg in *Physics of the Earth's Upper Atmosphere*, Eds C O Hines *et al*, Prentice Hall, New Jersey 1965)

$$I = I_\infty \, e^{-\tau} \tag{15}$$

Where 'I_∞' is the unabsorbed incident intensity.

The unit optical depth is obtained by putting τ=1 i.e., where the incident intensity gets reduced to 1/e of its initial value

$$\therefore \quad \tau = \sigma_a \, n \, H \sec\chi = 1 \tag{16}$$

For over head sun $\tau_{max} = \sigma_a \, n \, H = 1$, as $\sec\chi = 1$

The height at which τ_{max} occurs is known as the altitude of `unit optical depth' for over head sun

__Ionization efficiency__

The ionization efficiencies are usually limited by their total absorption cross-sections.

For atomic species $\sigma_a = \sigma_i$

$\therefore$The ionization efficiency is defined by

$$\eta_i = \frac{\sigma_i}{\sigma_a} = 1 \tag{17}$$

Whereas for molecular species $\sigma_i \leq \sigma_a$, therefore

$$\eta_i \leq 1 \tag{18}$$

Rate of Ion production by solar photons

The chapman theory:

The photo ionization of an atom or molecule takes place as a result of the action of a photon whose energy 'h_v' is equal to or greater than the ionization potential of the constituent X and an ion, electron pair gets created.

$$X + h\nu \rightarrow X^+ + e \tag{19}$$

The *'rate of production'* of the ion electron pairs can be expressed as a product of four terms

$$q = \eta \, \sigma_a \, n \, I \tag{20}$$

Where I is the intensity of the ionizing radiation at some level of the atmosphere and n, the concentration of the species that gets ionized. For a species to get ionized, it must first absorb the radiation according to its absorption cross section. If the flux of incident radiation is I (J/m^2s), the total energy absorbed per unit volume of the atmosphere per unit time is '$\sigma n I$'. However, not all this energy will go into the ionization process and the ionization efficiency η_i takes that into account., as it is the fraction of the absorbed radiation that goes into producing ionization.

The derivation made certain assumptions

1. The incident radiation is monochromatic so that 'σ' is constant
2. The atmosphere is horizontally stratified and Isothermal
3. The atmosphere is composed of a single species distributed with a constant scale height
4. Solar radiation is absorbed in proportion to the concentration of gas particles

The more general case of rate of ion production can be obtained from the Chapman formula by summing over all wavelength and all the ionizable species

The ionizing radiation (I) when incident at a solar zenith angle χ the ion production rate 'q' at any particular level is given by

$$q = \eta \, \sigma_a \, n \, I \qquad \text{or} \qquad \sigma_i \, n \, I \tag{21}$$

$$\text{Since} \quad \eta_i = \frac{\sigma_i}{\sigma_a}$$

Along a path length ds (=dh sec χ) the amount of incident photons dI absorbed by the gas is given by

$$dI = I \, \sigma_a \, nds = I\sigma_a \, n \, dh \sec\chi \tag{22}$$

$$\therefore \quad \frac{dI}{I} = \sigma_a \, n \, dh \sec\chi \tag{23}$$

Integrating

$$I = I_\infty \quad \exp\left(-\sigma_a \sec\chi \int_h^\infty n \, (h) \quad dh \right) \tag{24}$$

Substituting for I in the expression for q

$$q = \sigma_i \, n I_\infty \exp\left[-\sigma_a \sec\chi \int_{h'}^{\infty} n(h)\, dh\right] \tag{25}$$

In terms of optical depth τ,

$$q = \sigma_i \, n I_\infty \exp(-\tau) \tag{26}$$

The ion production rate ‘q’ is maximum when

$$\frac{dq}{dh} = 0 \quad \text{or} \tag{27}$$

when τ=1: for overhead sun or sec χ dependent for any other zenith angle

The height at which production ‘q_m’ occurs can also be worked out for an atmospheric density that decreases exponentially with the height for any χ as

$$\tau = \sigma_a \, n H \sec\chi \exp\left[\frac{-h_m - h_0}{H}\right] \tag{28}$$

or

$$\sigma_a n \, H \sec\chi = \exp\left(\frac{h_m - h_0}{H}\right) \tag{29}$$

h_0 is some reference altitude (usually above turbopause)

Taking logarithm on both sides

$$\frac{h_m - h_0}{H} = \ln(\sigma_a n H \sec\chi) \tag{30}$$

or

$$h_m = h_0 + H \ln(\sigma_a n H \sec\chi) \tag{31}$$

$$= h_0 + H \ln \sigma_a n H + H \ln \sec\chi \tag{32}$$

$$= h_0 + H \ln \left[\exp \frac{h_m - h_0}{H}\right] + H \ln \sec\chi \tag{33}$$

$$h_m = h_M + H \ln \sec\chi \tag{34}$$

Where h_M (unit optical depth altitude) is the height where q_M occurs for χ=0 and h_m is where q_m occurs for any χ angle

The above quation shows that the height h_M is the lowest for χ=0 and highest when χ=90 deg

h_M denotes the altitude of unit optical depth, which is equal to τ/e

q_m and q_M are related by

$$q_m = q_M \text{ Cos } \chi \tag{35}$$

where

$$q_M = \frac{\sigma_i}{\sigma_a} \frac{I_\infty}{eH} \tag{36}$$

$$= \frac{\eta_i I_\infty}{2.718\, H} \tag{37}$$

From the above it could be seen that 'q_m' depends on 'I_∞' and 'Cos χ' directly and on the scale height 'H' inversely, but does not depend on the number density of the ionizable constituent.

On the other hand h_m depends only on the unit optical depth, h_M, H and sec χ.

The altitude profile of 'q' could now be obtained from the above relations

$$q(h) = q_m \quad \exp\left[1-\frac{h-h_m}{H}-\sec\chi\exp\left(\frac{-h-h_m}{H}\right)\right] \tag{38}$$

or

$$q(h) = q_M \cos\chi \exp\left[1-\frac{h-h_m}{H}-\sec\chi\exp\left(\frac{-h-h_m}{H}\right)\right] \tag{39}$$

$$\textbf{If} \qquad \frac{h-h_m}{H} = Z$$

$$\underline{q(h) = q_M \quad \cos\chi\exp\left[1-Z-\sec\chi \ -\exp\left(-Z\right)\right]} \tag{40}$$

$$\frac{q(h)}{q_M} = \text{Cos}\,\chi\exp\left[1-Z-\sec\chi-\exp\left(-Z\right)\right] \tag{41}$$

$$\ln\frac{q(h)}{q_m} = \ln\,\text{Cos}\,\chi{+}\left[1-Z-\sec\chi-\exp\left(-Z\right)\right]] \tag{42}$$

The expression for 'q(h)' is known as the ***Chapman's ion production function.***

As anticipated the production rate is limited by shortage of ionizable gas at higher altitudes and shortage of ionizing radiation at lower heights. *The production rate maximizes when the optical depth is unity.*

The Chapman production function is important because its expresses fundamentals of ionospheric formation and of radiation absorption in any exponential atmosphere

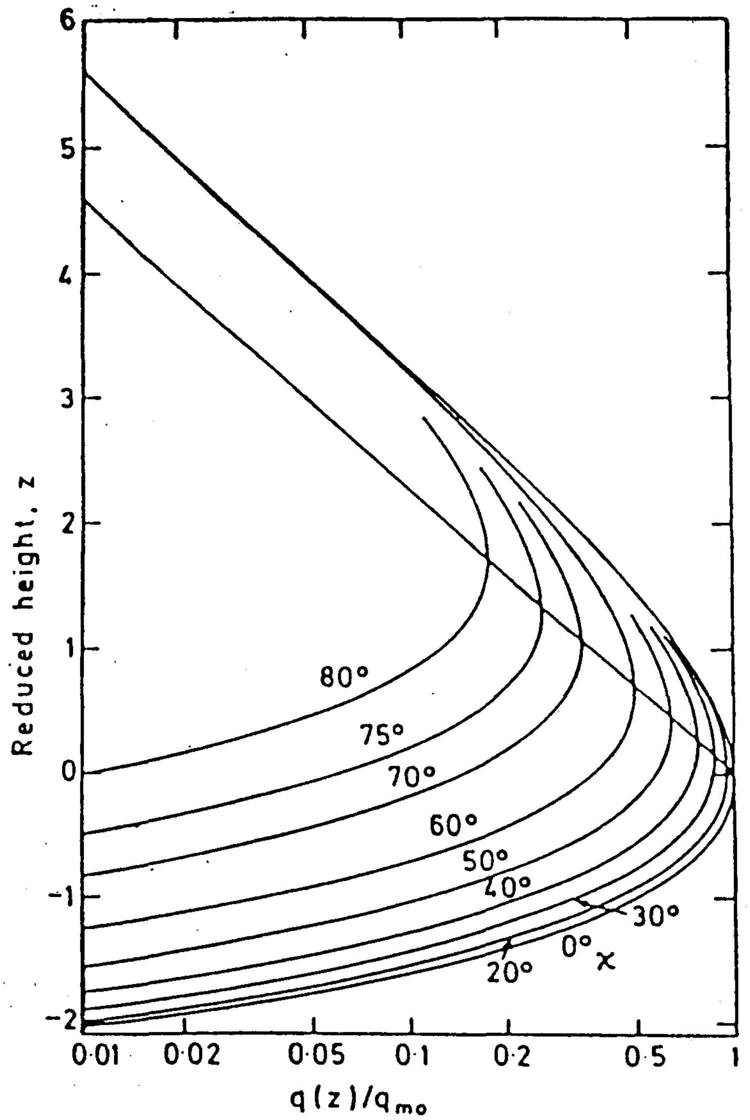


Fig. [illegible] Chapman production function. (After T. E. VanZandt and R. W. Knecht, in *Space Physics* (eds. LeGalley and Rosen). Wiley, 1964)

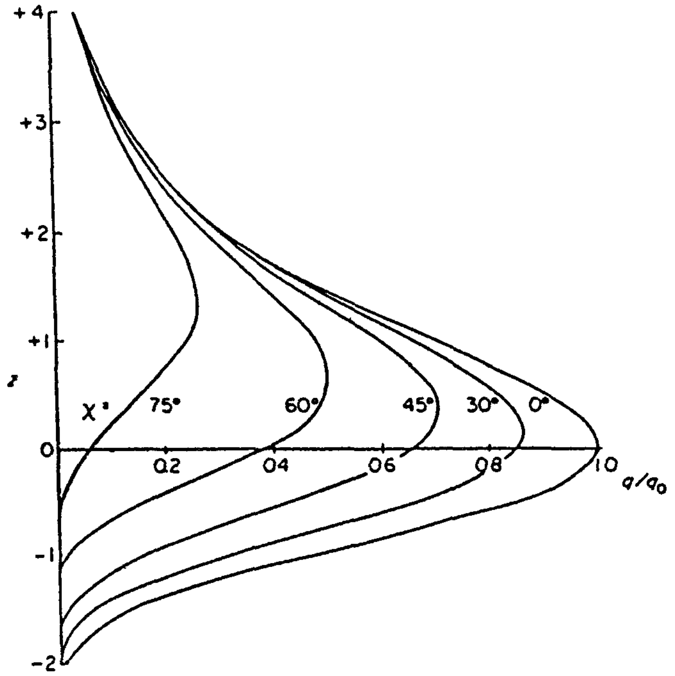


Fig Normalized Chapman production function versus reduced height z, parametric in solar zenith angle χ [Eq (319)]

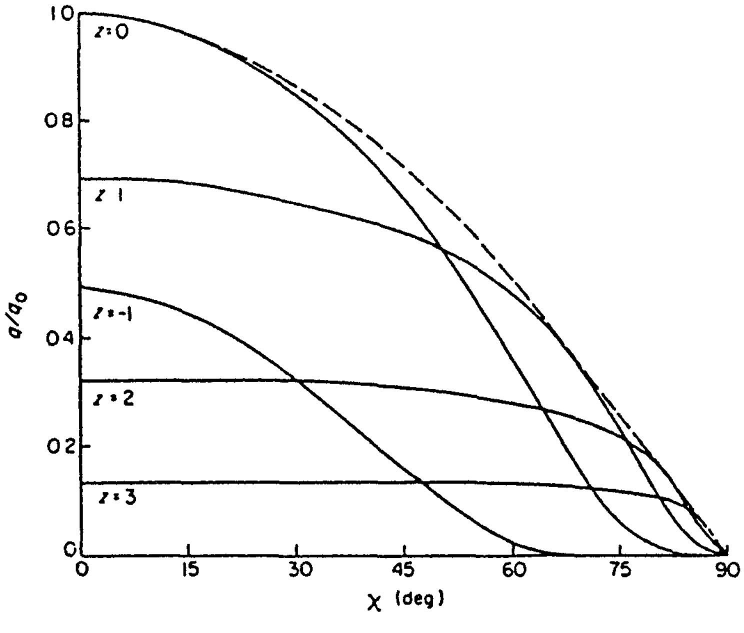


Fig Normalized Chapman production function versus solar zenith angle χ, for several values of reduced height z [Eq (319)] The broken line is the envelope, $q_1/q_0 = \cos\chi$

The Chapman function Ch (χ)

A consequence of flat stratified atmosphere assumption is that, when χ exceeds 75°, sec χ starts diverging and becomes infinite when χ = 90°. Therefore it is necessary to replace sec χ by the Chapman function Ch (χ) which takes into account the sphericity of the planet and its atmosphere. The function is defined as the ratio of the total content of the atmosphere in line of the sight (l) to the sun and the vertical column content.

$$\mathrm{ch}(\chi) = \frac{\int_{e}^{\infty} n\,(l)\,dl}{\int_{h}^{\infty} n\,(h)\,dh} \tag{45}$$

Actual Photo Ionization rate

Using the photon flux values at the top of the atmosphere and also the ionization and absorption cross sections of the major atmospheric constituents N_2, O_2 and O in addition to the Chapman formula, the ion production rate can be calculated as

$$q = \sum_{j\lambda} \sigma_{ij}\, n_j\, \phi_\infty\,(\lambda) \exp - \sum_{k} a \int_{h}^{\infty} n_k \sec\chi\, dh \tag{46}$$

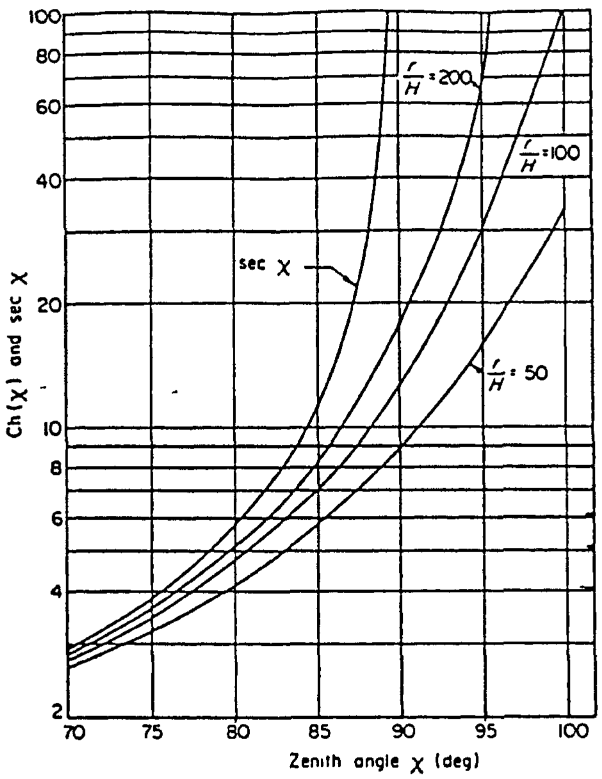


Fig. The function $\mathrm{Ch}(\chi)$ for three values of r/H (where r = geocentric distance, H = atmospheric scale height) compared with sec χ

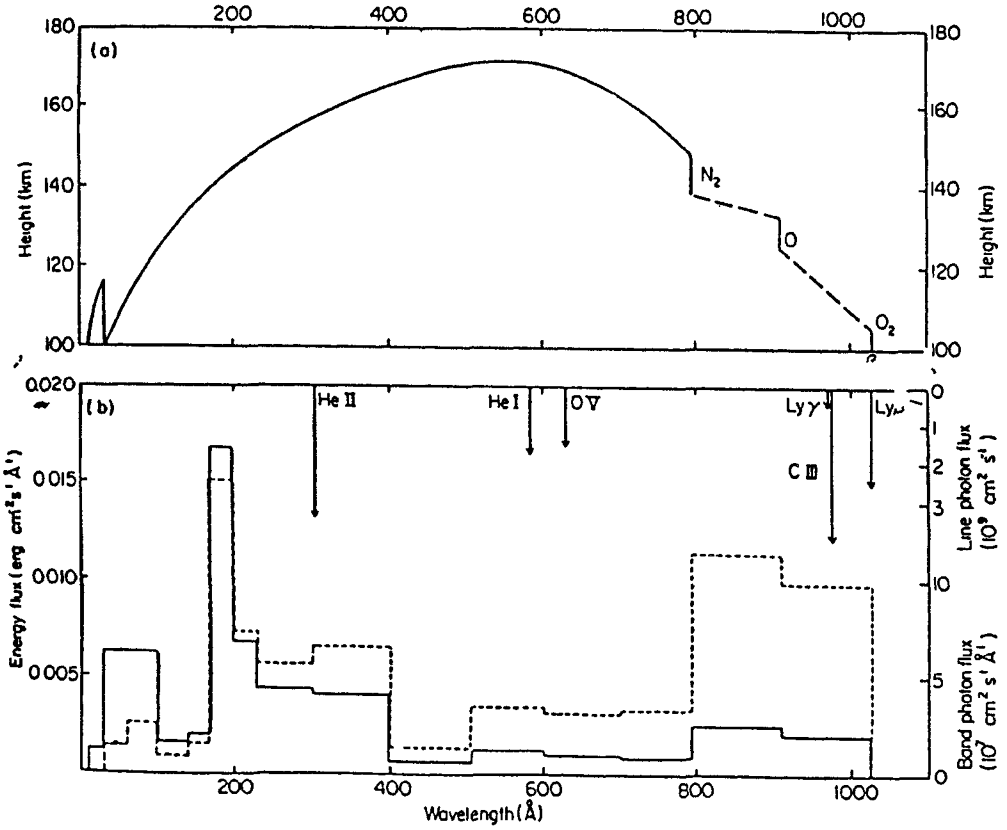
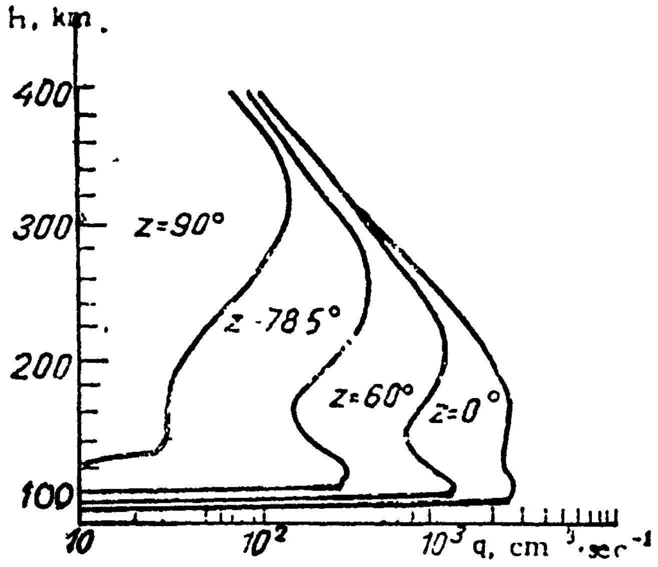
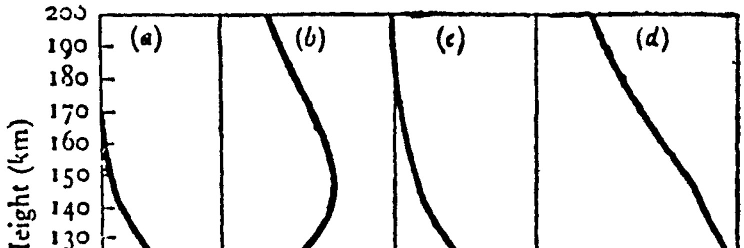
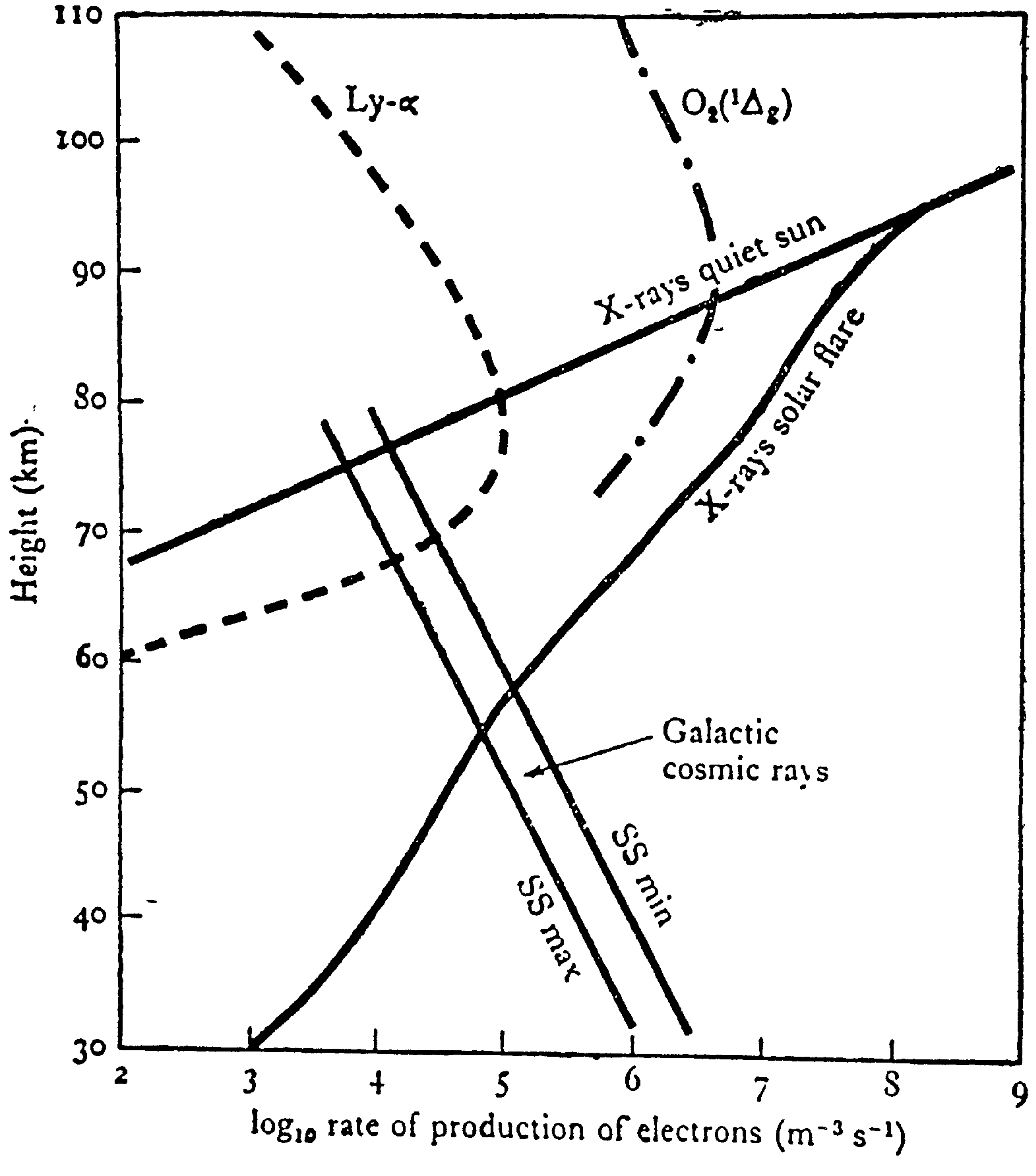


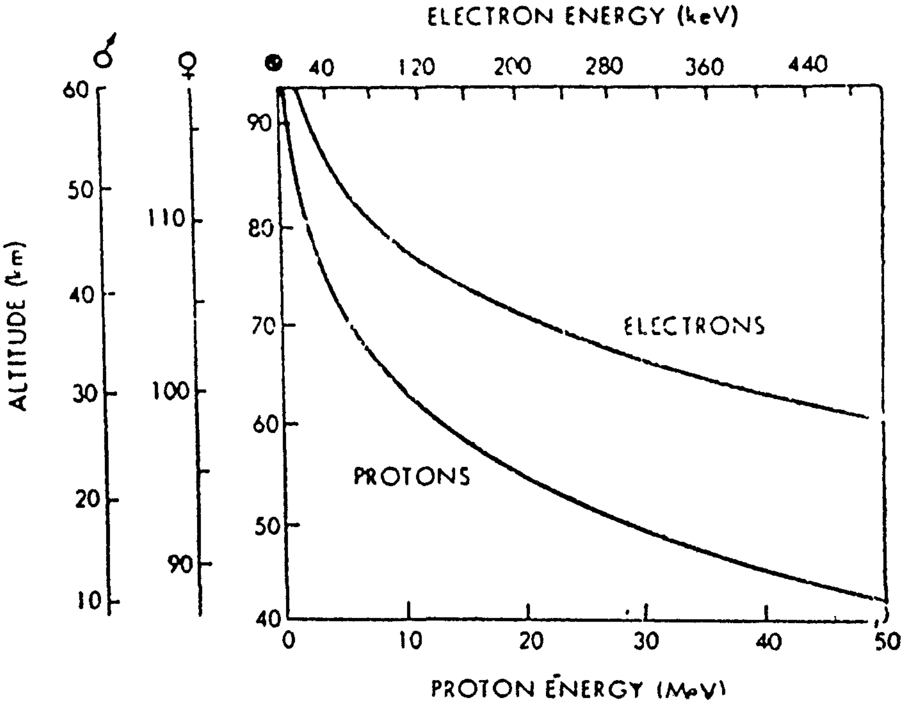
Fig (a) Height of unit optical depth for vertically incident radiation, as a function of wavelength The break at 31 Å corresponds to the K absorption limit of N_2; those at 796 Å, 911 Å, and 1027 Å to the ionization limits of N_2, O, O_2, respectively (b) Solar flux for a moderate level of activity (sunspot number $R \simeq 60$), for several wavelength bands between 8 and 1027 Å. The area below the broken lines indicates photon flux; the area below the full lines indicates energy flux. The photon flux contained in some important spectral lines are indicated by the lengths of the arrows [based on data of Allen (1965) and Norton *et al* (1963)] [*Note* 1 erg $\mathrm{cm^{-2}\,s^{-1}\,Å^{-1}} = 1\ \mathrm{mW\,m^{-2}\,Å^{-1}}$]





a) λ < 140A b) λλ 140-800A c) λ > 1027A


110
100
90
80
70
60
50
40
30
Height (km)
2
3
4
5
6
7
8
9
log10 rate of production of electrons (m-3 s-1)
Ly-α
O2(1Δg)
X-rays quiet sun
X-rays solar flare
Galactic cosmic rays
SS min
SS max


ELECTRON ENERGY (keV)
♂
♀
⊕
40
120
200
280
360
440
60
50
40
30
20
10
110
100
90
90
80
70
60
50
40
ALTITUDE (km)
ELECTRONS
PROTONS
0
10
20
30
40
50
PROTON ENERGY (MeV)

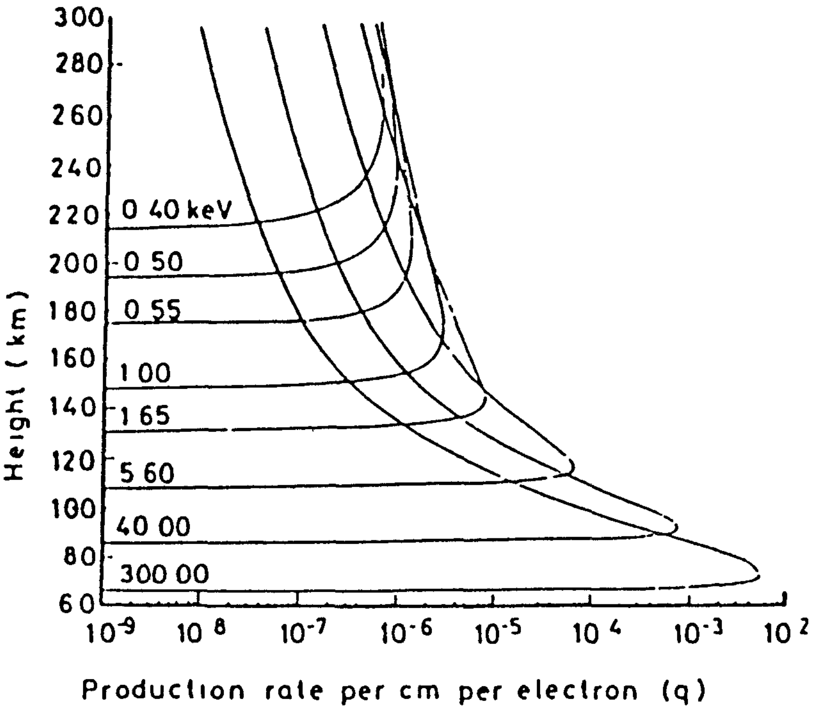


Fig Production rates due to monoenergetic electrons of various initial energy (After M H Rees, *Planet Space Sci* 11, 1209, copyright (1963) Pergamon Press PLC)

Ionization due to the particle bombardment:

Galactic cosmic rays and solar cosmic rays (during solar photon events), solar wind protons and low energy electrons and also protons from within the magnetosphere, produce some ionization at the lower level of the atmosphere (<50km)

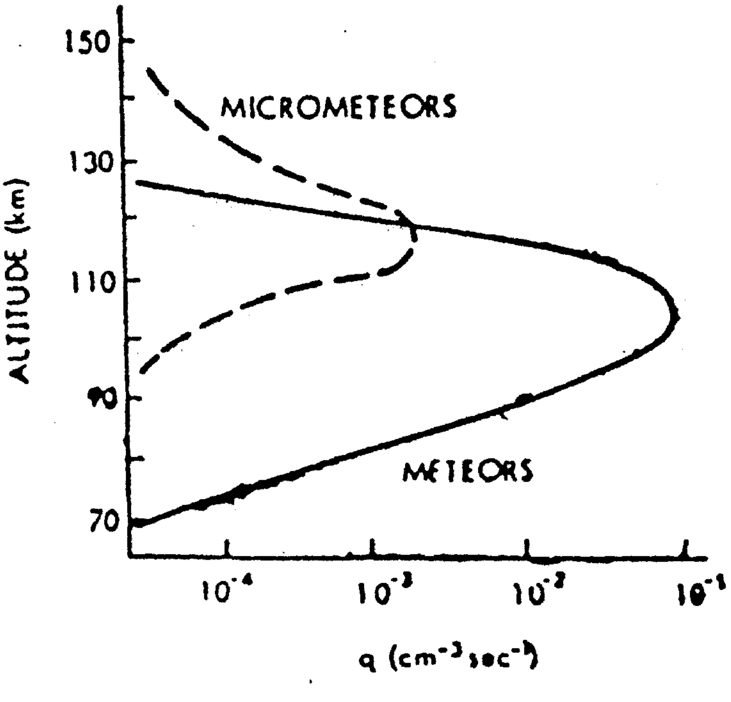
Galactic cosmic rays are important only during nighttimes as it is over powered by the solar XUV radiation during daytime.

Relativistic solar cosmic rays (protons) emitted during large flares produce substantial ionization in the polar caps causing the phenomenon of Polar Cap Absorption (PCA)

The magnetic shield prevents such high-energy charged particles from entering into the equatorial and low latitudes. (Figure: penetration depths in different planets)

Ionization due to meteors:

As meteorites speed past the atmospheric regions a small amount of ionization is produced The peak ionization is produced around 105km at a rate of ~0 1cm^{-3} s^{-1}. Though the amount is small because of their long lifetime they tend to get accumulated and sometimes could become very significant in the E-region


150
130
110
90
70
ALTITUDE (km)
MICROMETEORS
METEORS
10^{-4}
10^{-3}
10^{-2}
10^{-1}
q ($cm^{-3}sec^{-1}$)

Electron density distribution with height

Having studied how the ion-electron production varies with height, we now analyze how they are distributed with height. This is because the electron density at any height is decided by its production and loss rates, which occur simultaneously. Hence the shape of the density distribution would be totally different from the production curves

The distribution of ionization in the ionosphere at any instant is governed by the *'continuity equation'*

Where N is the electron number density, 'q', the production rate and L (N), the rate of loss which depends on N and div (NV) represents the transport out of a given volume with V, the drift velocity in addition to the random velocity

A steady state situation $\frac{dN}{dt} = q - L(N) - \mathrm{div}\,(NV)$ can often be assumed except during near sunrise, sunset and during eclipses when N changes rather rapidly with time. Otherwise it is usually true at all heights and the electron distribution can be worked out during daytime (quasi equilibrium)

The transport term could be split as

$$\operatorname{div}(N\mathbf{V}) = N \operatorname{div} \mathbf{V} + \mathbf{V} \cdot \nabla N \qquad (47)$$

Which implies that N can charge because of changes in velocity (V) or due to the gradient in N across the volume

Because `grad N' is mostly in the vertical direction it is the vertical component 'W' of **V** that is important in determining the magnitude of div (NV)

The rate of removal of 'N' by transport can be expressed as

$$\frac{dN}{dt} = \frac{d}{dh}(NW) = N\frac{dW}{dh} + W\frac{dN}{dh} \qquad (48)$$

Which means that the movement is controlled by the vertical gradient in velocity and the electron density

The movement may be caused by diffusion, electric and magnetic fields and or neutral dynamics (winds)

The continuity equation may be written as

$$\frac{dN}{dt} = q - L(N) - \frac{d}{dh}(NW) \qquad (49)$$

Under quasi-equilibrium conditions during daytime and also when the electron concentration has reached a diurnal maximum, $\frac{dN}{dt}=0$, and also if there are no movements W=0
then

$$q = L(N) \qquad (50)$$

This is true when the ionosphere is in *'chemical equilibrium'* or when

$$L(N) >> \frac{d}{dh} NW)$$

When L(N)<< $\frac{d}{dh}$ (NW), then `q' is balanced by the drifting away of electrons from the place where they are produced

$$q = \frac{d}{dh}(NW) \qquad (51)$$

is the condition for *'drift equilibrium'*

So, if the electrons, before getting lost,

move by a distance of one scale height, then the drift term is important in determining its redistribution. On the other hand, if the electron is destroyed before it can move that far, the loss term in the continuity equation plays an important role and the distribution is essentially in chemical equilibrium

The electron distribution will be in diffusive equilibrium when div (NV)= 0 and $\frac{dN}{dt} \neq 0$. This will happen when the electrons are distributed according to

$$N = N_o \exp\left(- \frac{h - ho}{H_D}\right) \qquad (52)$$

Where H_D is the scale height of the dominant ion species at that level

The 'diffusive equilibrium' situation for electrons usually prevails above the F-region maximum in the ionosphere. In this region photochemical processes can be neglected.

The electron-ion production rate 'q' will be zero at night if we assume that solar radiation is the only source of ionization and if W = 0 then the continuity equation reduces to

$$\frac{dN}{dt} = L\,(N) \qquad (53)$$

which implies that in the absence of production and transport, the electron density decays with time dictated by the 'loss process' alone

There are two `main' loss processes in the ionosphere involving recombination of ionization where electrons are lost by recombining with positive ions, so that

$$L\,(N) = \alpha\,[N_e]\,[N_i] \qquad (54)$$

Where α is the recombination coefficient. Since charge neutrality criterion demands N

$$N_e = N_i \qquad (55)$$

$$L\,(N) = \alpha\,[N_e]^2 \qquad (56)$$

$$\frac{dN}{dt} = -\,\alpha\,[N_e]^2 \qquad (57)$$

(Square dependence)

This loss process is dominant in the ionosphere below 200km. If the electron density is N_o at t = 0 then its density N at time t is obtained as

$$\frac{1}{N} - \frac{1}{No} = \alpha\,t \qquad (58)$$

Taking the production rate 'q' from the Chapman production function one obtains

$$N = N_0 \exp 1/2 \left[1 - Z - \sec\chi\, e^{-z}\right] \qquad (59)$$

In which $z = (h - ho)/H$ and the electron density at the peak of the layer varies as $\mathrm{Cos}^{1/2}\chi$

$$N_m = N_0 \,\mathrm{Cos}^{1/2}\chi \qquad (60)$$

A layer with these properties is called an <u>'α - Chapman layer'</u>

In the lower ionosphere, one encounters significant number of negative ions too Charge neutrality then would require

$$[N_e] + [N_-] = [N_+] \tag{61}$$

Negative and positive ions also could recombine with their own corresponding recombination coefficient

$$q = \alpha_e [N_e][N_+] + \alpha_i [N_-][N_+] \tag{62}$$

The ratio between negative ion and electrons is represented by $\lambda =$ $[N_-]$ / $[N_e]$ =

$$[N_-] = \lambda [Ne] \quad \text{and} \quad \therefore \quad [N_+] = [N_e] + \lambda [N_e] = N_e (1 + \lambda) \tag{63}$$

$$\cdot \quad q = (1+\lambda)(\alpha_e + \lambda \alpha_i)[N_e]^2 \tag{64}$$

Which in cases where $\lambda\alpha_i = \alpha_e$ becomes

$$q \; (1+\lambda) \; 2\alpha \; [N_e]^2 \tag{65}$$

In the presence of negative ions, the equilibrium electron density is still proportional to the square root of the production rate but the magnitude is changed

The term $(1+\lambda)$ $(\alpha_e + \lambda\alpha_i)$ is called the 'effective recombination coefficient'

Linear loss type:

Here the loss rate L(N) is directly proportional to the electron concentration [N_e]

$$L(N) = \beta N \tag{66}$$

$$\frac{dN}{dt} = -\beta N \quad \text{or} \quad N = N_o \exp(-\beta t) \tag{67}$$

Here the electron density N decays exponentially with a time constant (1/β) during night time when q=0. This process is prevalent at altitude >200km

Under quasi equilibrium conditions and in the absence of transport, the continuity equation for the electron density during daytime are

$$q = \beta N \tag{68}$$

Taking Chapman production function

$$N = \frac{q}{\beta} N_m \exp\left[1 - Z - \sec\chi \exp(-Z)\right] \tag{69}$$

$$\left[N_m = \frac{q_m}{\beta} = \frac{\eta\,\phi_\infty \operatorname{Cos}\chi}{2.718 H\beta}\right]$$

In this case the peak electron density now varies as

$$N_m = N_o \operatorname{Cos}\chi \tag{70}$$

Such a layer is referred to as a Chapman β- layer

Note:

In the square loss region N_{max} occurs at the same height of production max and varies as $\sqrt{\cos}\,\chi$ whereas in the linear loss region N_m varies as $\cos\chi$ but occurs at a level much above the level of maximum ion production determined by diffusion

<u>Explanation:</u>

The dominant neutral species >150km is atomic oxygen. The production of ionization depends on the [O] density with height, i.e., 'q' would decrease according to the scale height of atomic oxygen. But the loss process, which is a two step process depends on the concentration of $[N_2]$ and $[O_2]$ i.e.,

$$O^+ + N_2 \quad - \quad NO^+ + O \qquad (71)$$

$$O^+ + O_2 \quad - \quad O_2{}^+ + O \qquad (72)$$

This loss channel is considerably faster than the direct recombination. Hence 'β' can be written as

$$\beta = kn\,[N_2] \text{ or } kn\,[O_2] \qquad (73)$$

where k is the reaction constant

β decreases faster with height and is either controlled by the scale height of N_2 or O_2, as compared to 'q'

N which is equal to q/β steadily increases with height and does not peak itself

This increase in 'N' is controlled by 'diffusion' at some height where the diffusion time constant $\tau_D \le \tau_C$ and the peak density N_m is formed where $\tau_D = \tau_C$

Loss processes :

a) *Electron – ion recombination*

Radiation recombination

Here an electron and an ion recombine to produce a neutral atom in an excited state and emits a quantum of radiation as

$$X^+ + e \rightarrow X^* + h\nu \qquad (74)$$

This is an extremely slow process $\alpha_{rad} = 10^{-12}$ cm^{3}s^{-1} and typically varies with temperature as $T^{0.75}$.

Since $\tau = 1/\alpha N$, the time constant is very large

Dissociation recombination

Here the molecular ions like NO^+, O_2^+ etc get dissociated into their respective atoms

$$XY^+ + e \rightarrow X^* + Y^*$$
$$\rightarrow X + Y + \Delta E \text{ (energy)} \qquad (75)$$

'α_D' is of the order of 10^{-7} cm^3 s^{-1} and is efficient and varies with temperature as $T_e^{-1/2}$ to $T^{-3/2}$ (may also depend on T_i – due to the vibrational state of the molecule)

Ion – ion recombination:

In the lower regions i.e., <90km negative ions replace the electrons (electron attachment)

e.g; $O_2 + e + M \rightarrow O_2^- + M$ **(76)**

These negative ions subsequently disappear by combining with positive ions by ion-ion recombination as

$$O_2^- + X^+ \xrightarrow{\alpha_{ii}} O_2 + X^* \qquad (77)$$

The reaction coefficient α_{ii} is of the order of $10^{-7} cm^3 s^{-1}$
In addition to this, there are processes known as

Collisional detachment	$O_2^- + M \rightarrow O_2 + M + e$	(78)
Associative detachment	$O_2^- + O \rightarrow O_3 + e$	(79)
Photo detachment	$O_2^- + h\nu \rightarrow O_2 + e$	(80)

Charge transfer reactions:

Very important in the F region: generally of two types:

$O^+ + N_2 \rightarrow NO^+ + N$ **(81)**

$O^+ + O_2 \rightarrow O_2^+ + O$ **(82)**

Which later recombine through dissociative recombination

$NO^+ + e \rightarrow N + O$ **(83)**

$O_2^+ + e \rightarrow O + O$ **(84)**

These reactions are important in the regions where the molecular densities are larger i.e., ~200km

<200km; though molecular densities are larger, [O^+] concentration is smaller
>200km O^+ is larger but [N_2] and [O_2] are smaller

Infact, larger the separation between the production height (170 – 180km) and the loss level (200-220km) during daytime in the F-region, more distinct is the formation of the F_1 layer at 180km

Vertical transport:

The final term in the continuity equation corresponds to bulk movement of the ionospheric plasma. In the absence of production and loss the continuity equation is written as

$$\frac{dn}{dt} = -\operatorname{div}(NV) \tag{85}$$

Considering only the vertical movements

$$\frac{dn}{dt} = -\frac{\partial}{\partial h}(NW) \tag{86}$$

Where 'W' is the vertical component
If the drift is due to 'Diffusion' then

$$W = \frac{D}{N}\,\frac{\partial N}{\partial h} \tag{87}$$

D being the 'diffusion coefficient', given in its simplest form $D = kT/m\nu$ where k is the Boltzman's constant

The expression for 'D' is derived by equating the driving force due to pressure gradient to the drag force due to collisions as the minority gas diffuses through the stationary majority gas. In this case the minority gas is the ionospheric plasma and the majority gas is the neutral air. Moreover for drift in the vertical direction, the force of gravity also acts on each particle, giving

$$\frac{-dP}{dh} = Nmg + N\nu m w = \frac{-kT\,dN}{dh} \tag{88}$$

Where the relation $P = N\,kT$ has been used

$$\textbf{Since } D = \frac{kT}{m\nu} \quad \text{and} \quad H = \frac{kT}{mg} \tag{89}$$

$$NW = -D\left(\frac{dN}{dh} + \frac{N}{H}\right) \tag{90}$$

Substituting in the continuity equation

$$\frac{dN}{dt} = \frac{\partial}{dh}\left[D\left(\frac{dN}{dh} + \frac{N}{H_s}\right)\right] \tag{91}$$

This equation has to be satisfied by the time and height variation of the upper F-region and higher above where typically the ion production and recombinations are extremely small.

The actual height distribution is given by the *<u>distribution height</u>* defined as

$$\delta = \left(\frac{-1}{N}\frac{dN}{dh}\right)^{-1} \tag{92}$$

At equilibrium δ is equal to the scale height since dN/dt = 0 which gives (dN/dh + N/H) = 0 and hence $\delta = H$

Both the E (105 – 110) and F_1 (160-180) regions are fairly well understood. The E-region is formed by the less strongly absorbed and therefore more penetrating EUV radiation (800-1027A) and X-radiation 10-100A. The primary ions are N_2^+, O_2^+ and O^+. However most numerously observed ions are NO^+ and O_2^+. The loss is mainly due to dissociation recombination

On the other hand the F_1 region is attributed to the most heavily absorbed part of the solar spectrum between 200-900A, with production maximizing around 140-170km. The primary reaction produces N_2^+, O_2^+, O^+, He+ and N^+, but subsequent reactions leave NO^+ and O_2^+ as the most abundant. Higher above O^+ dominates.

The loss is through a two step process and is essentially controlled by the Dissociative recombination

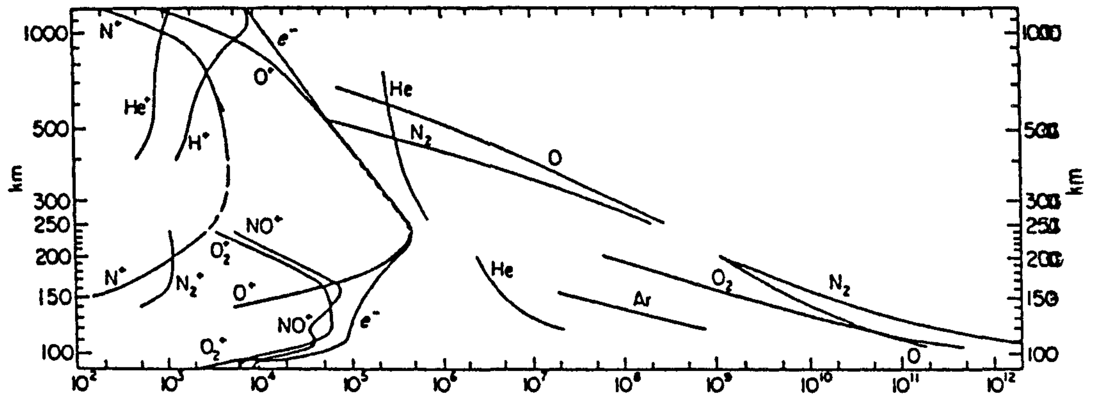


Fig. 6. IQSY daytime ionospheric and atmospheric composition, based on mass spectrometer measurements. Ion and neutral distributions below 250 km are from two daytime rocket measurements above White Sands, New Mexico (32°N, 106°W). The helium distribution is from a nighttime measurement. Distributions above 250 km are from the Elektron II satellite results of Istomin (1966) and Explorer XVII results of Reber and Nicolet (1965) [C. Y. Johnson, U.S. Naval Research Laboratory, Washington; reprinted from "Ion and neutron composition of the ionosphere," by C. Y. Johnson, in "Annals of the IQSY," Volume 5, 1969, by permission of the M.I.T. Press, Cambridge, Massachusetts. Copyright 1969 by M.I.T.]

Depiction of these layers in a typical 'Ionograms'

During night hours, the electron densities decrease by an order of magnitude and hence the D, E and F_1 regions become insignificant

The portion below the F_2 peak is referred to as the '*bottom side*' of the ionosphere and above the '*topside*'. More than 6 decades of ionospheric sounding – Morphology studied.

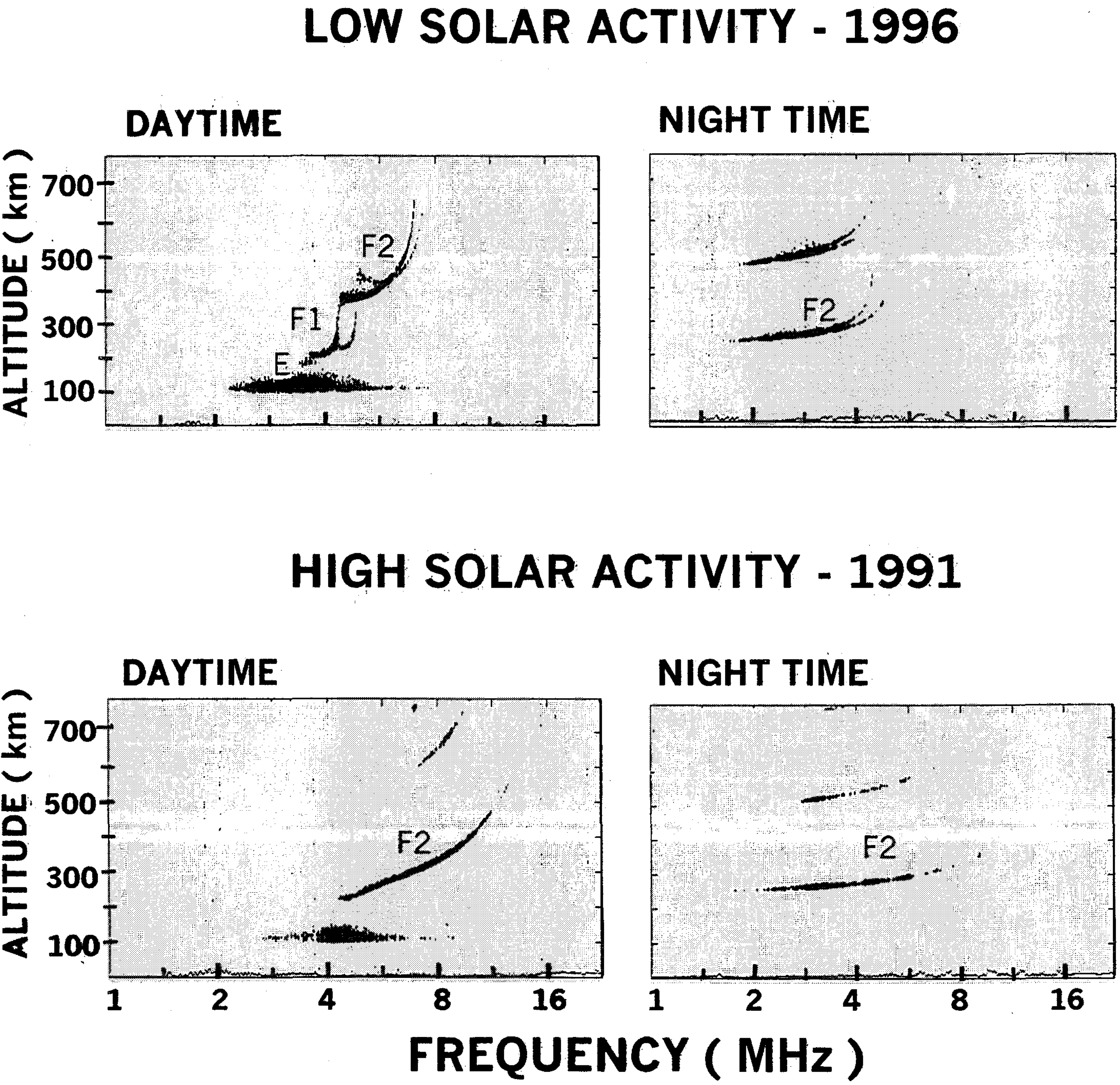
Ionogram – max density at each E, F_1 and F_2 layers could easily be obtained from the 'critical frequency' or the penetration frequency obtained from the ionograms f_oE, f_oF_1 and f_oF_2. The relation between the frequency of reflection and the plasma density is

$$N = 1.24 \times 10^4 f_N^2 \quad \textbf{(114)}$$

Where f_N is in MHz and N the corresponding density

For obtaining information on the topside, satellites-carrying ionosondes have to be made use of.

D region densities could be obtained only by either using partial reflection techniques and/or rocket borne techniques.



LOW SOLAR ACTIVITY - 1996

HIGH SOLAR ACTIVITY - 1991

Ionospheric Regions and its extent:

After considering the physical principles governing the intensity and form an ionospheric layer, it could be realized that in order to work out the actual ionosphere on earth or any other planet one should consider several factors. One should know the composition and also other parameters like density and temperature. We should also know the solar spectrum and energetic particle fluxes that could cause ionization. We should be able to determine what gases could be ionized and also the ionization rate of each species, sum over all wavelengths and gases to get the total production rate in a given volume. Then the loss processes have to be considered both chemical and transport. In cases where minor species are important, it becomes very difficult to comprehend.