

Space Science: Atmosphere

Part -2

Thermal Structure

Review tropospheres

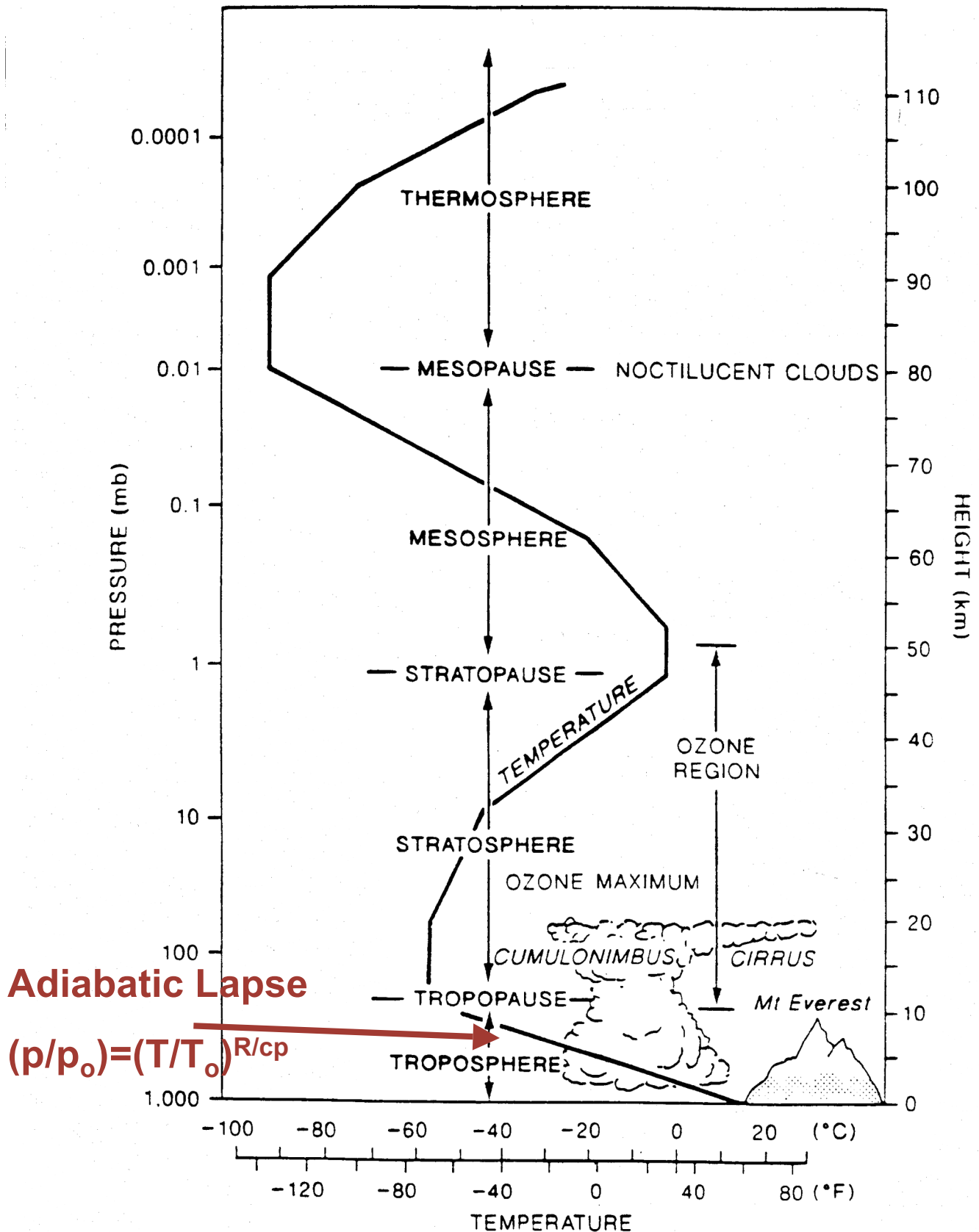
Absorption of Radiation

Chapman Layer

Rate Equations

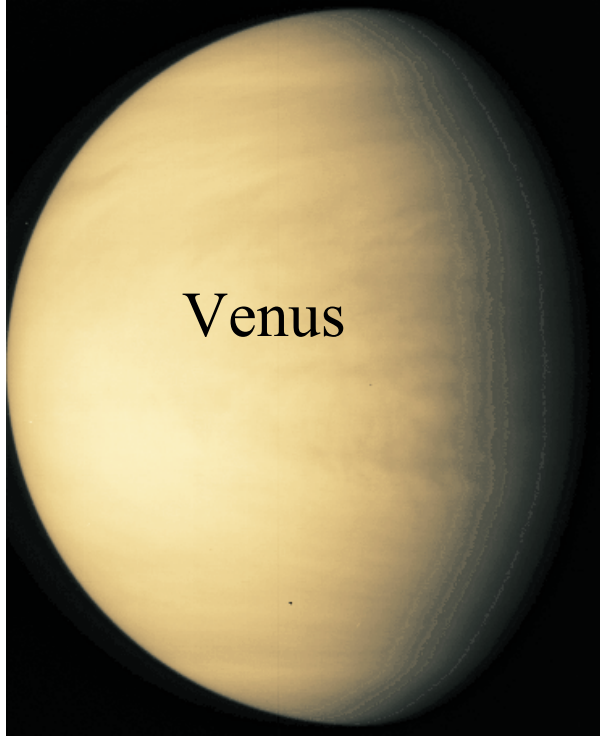
Ozone Layer

Earth's T(z): another view



Where is T_e (Radiation to space)? ~250K

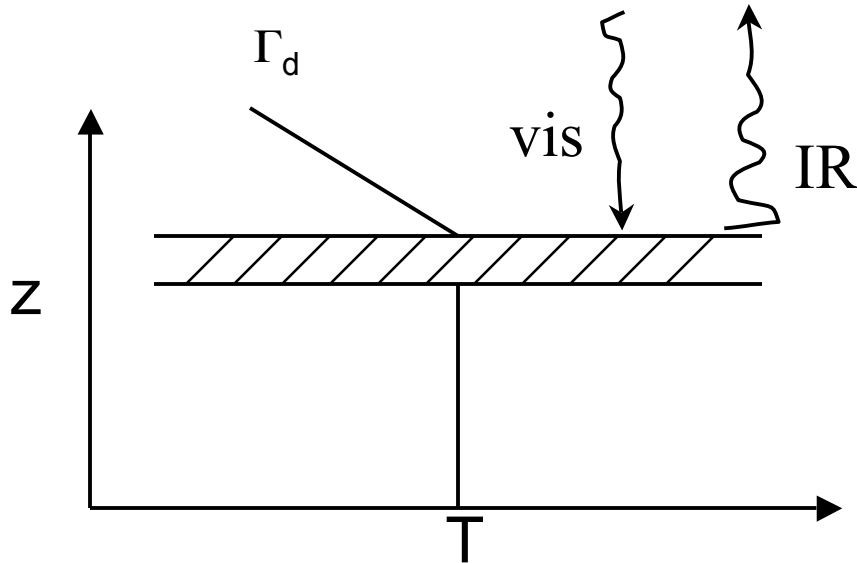
'Terrestrial' Bodies



Should have included Triton

Heating at a Cloud Layer

A model for Venus?



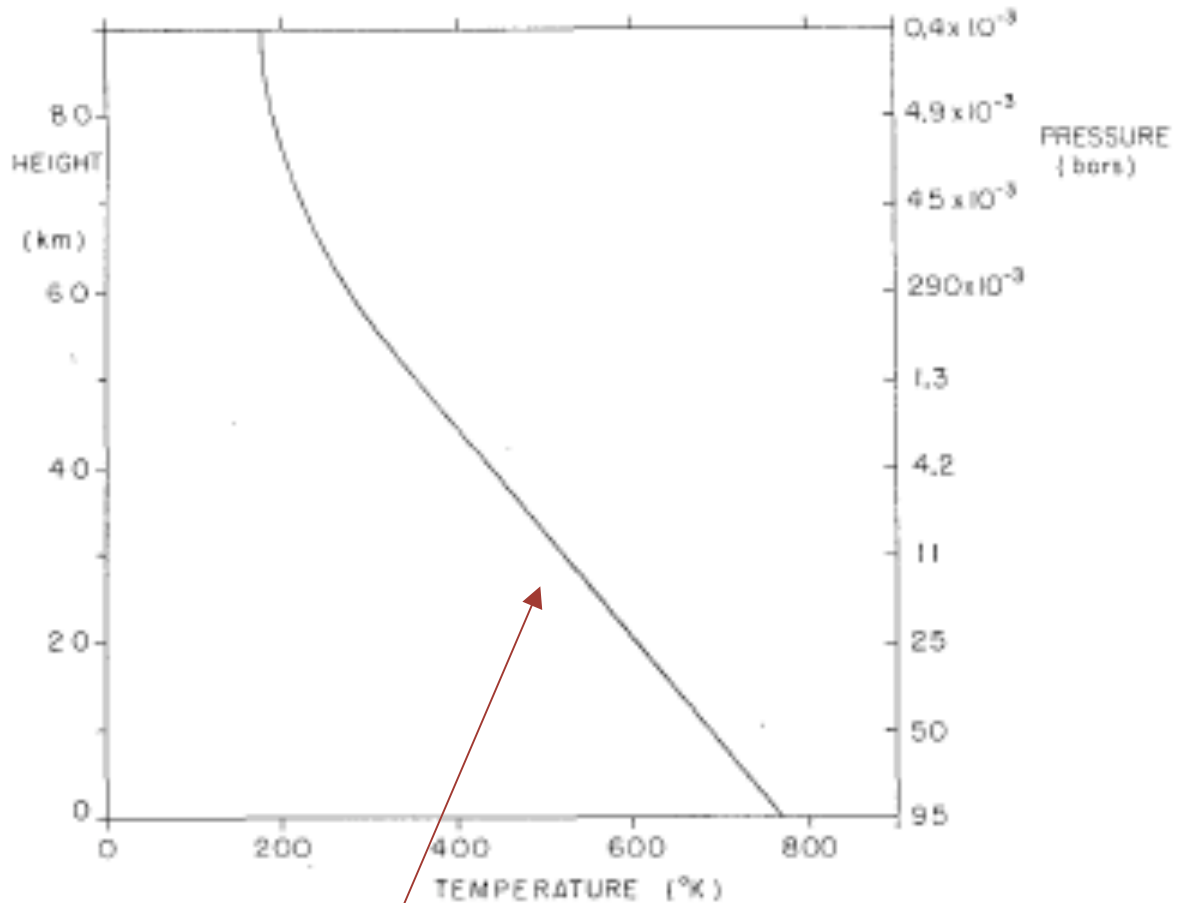
Venus is cloud covered

Assume sunlight absorbed in clouds, not surface
IR re-radiated to space, then a simple model gives:
Adiabatic Lapse rate above and isothermal below

But Venus was found to have an increasing temperature with decreasing altitude below the cloud layer.

Therefore, some radiation must get through

Venus: Troposphere Measured

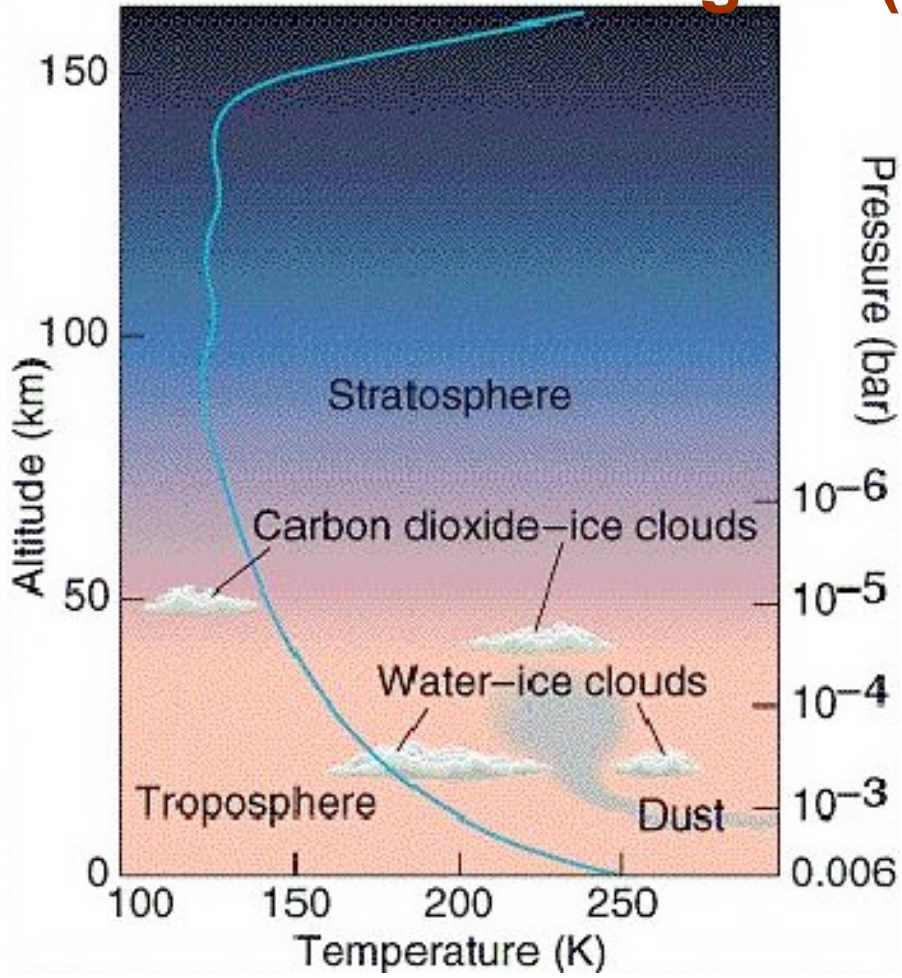


Adiabatic Lapse Rate

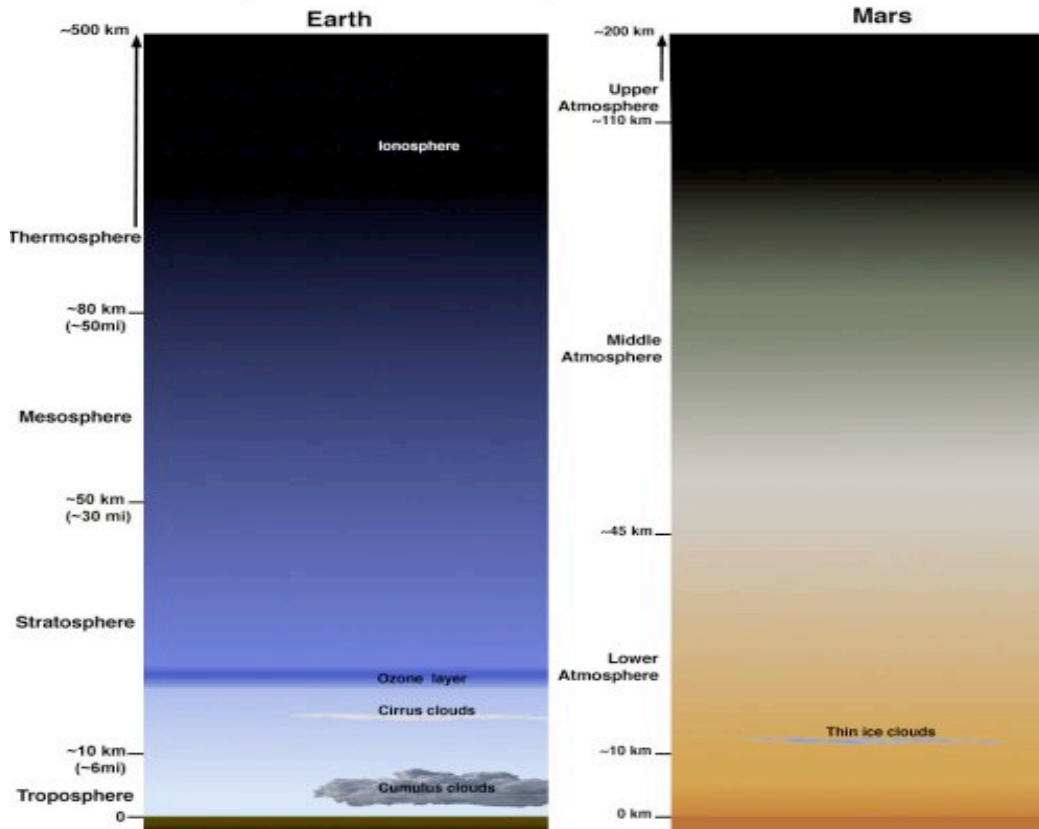
$$\Gamma \sim 9 \text{ K/km}$$

Slightly smaller than our estimate
Pressure ~3000ft under ocean surface
Was it ever Earth-like?

Mars Global Average: T(z)

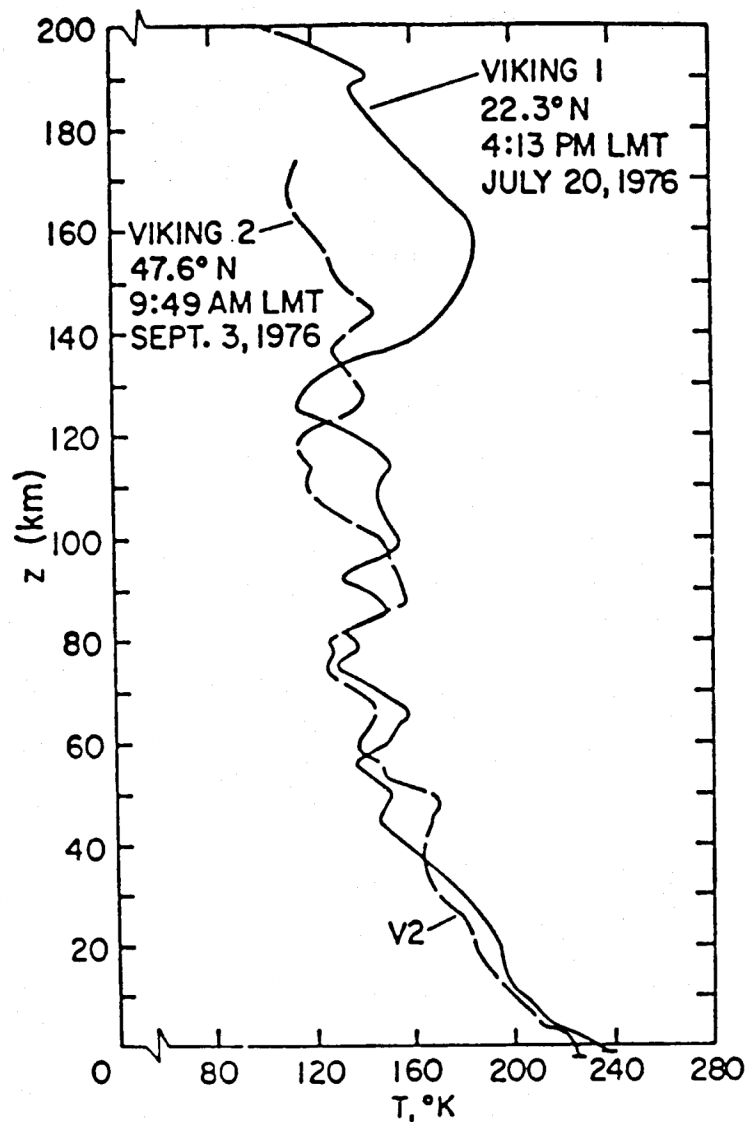


A Comparison of the Atmospheres of Earth and Mars



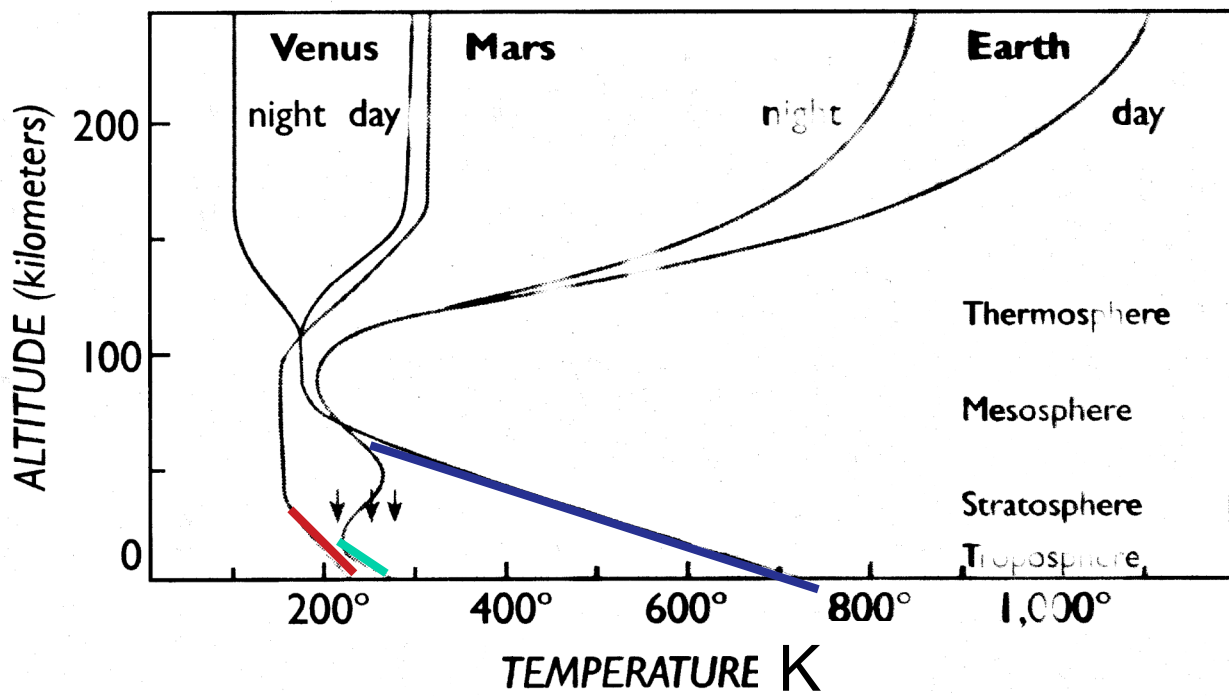
What Mars $T(z)$ is Really Like!!

Locally: Viking Measurements



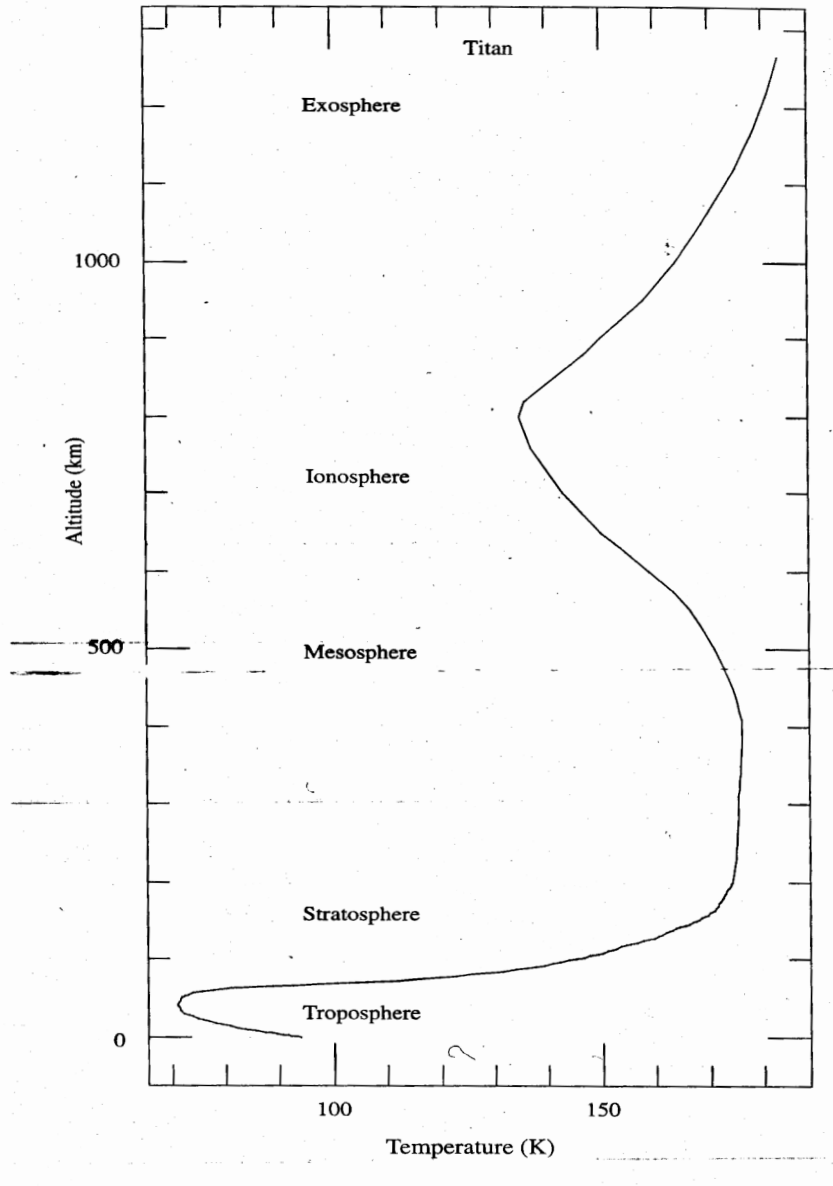
Atmospheres have wave-like propagation also

Venus, Earth Mars: $T(z)$ Comparison



Titan's Atmosphere

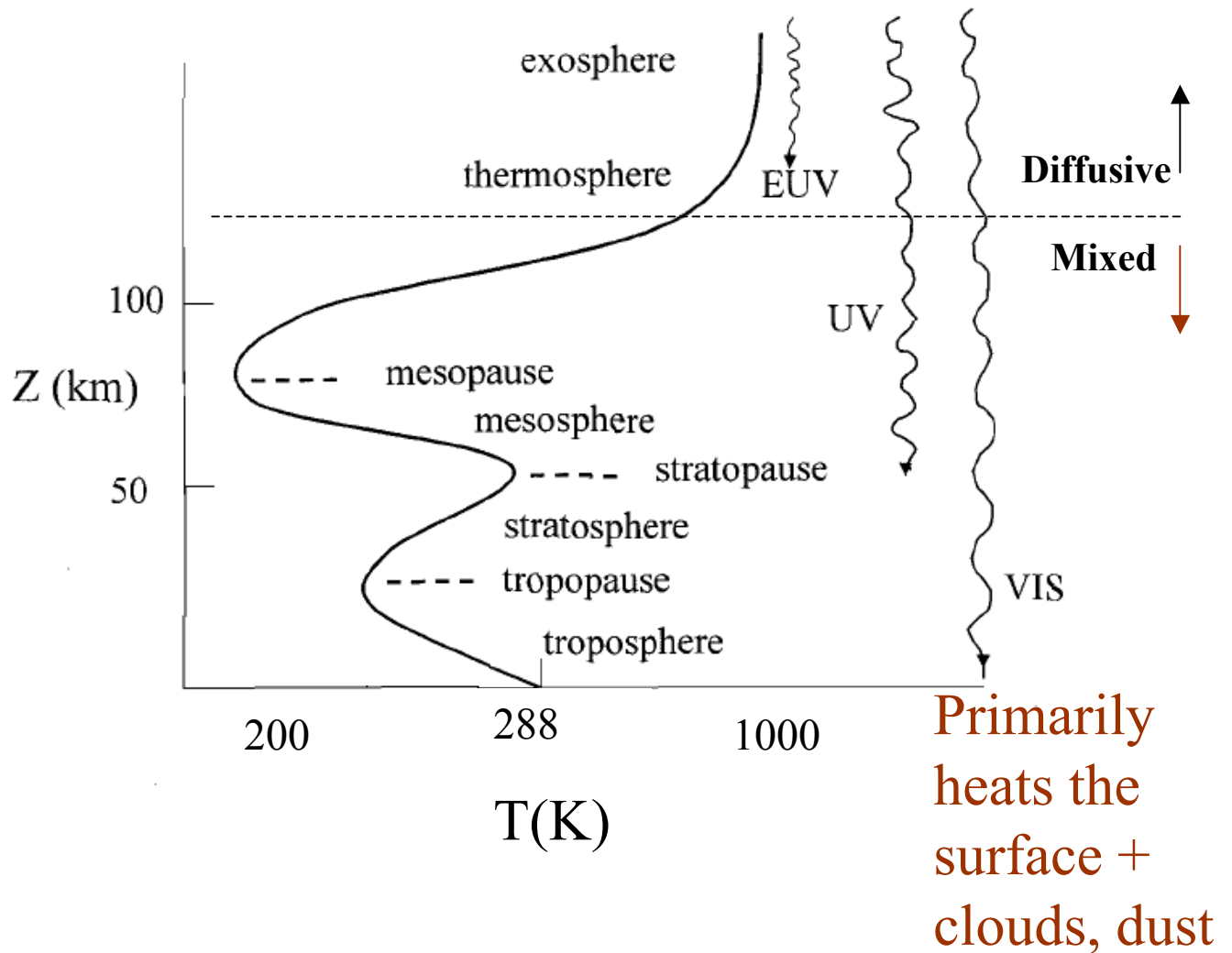
(d)



Temperature vs. Altitude

Earth's Atmosphere is *Layered*

Radiation Absorption Indicated



Layers give the names

Temperature (Heat) vs. Altitude

Radiation absorption+ heat transport

Bottom: *Troposphere* →

Heat Surface (Visible Light)

+ Convective Transport (Lapse Rate)

+ Some Radiative Transport

Middle: *Stratosphere and Mesosphere* →

Near UV Absorption

+ Radiative Transport

Top: *Thermosphere* →

Far UV absorption

+ Conduction Dominates

Radiation Absorption

Mesosphere and Stratosphere Radiative Transport

ABSORPTION of LIGHT

Wavelength	~eV	Effect
0.1cm	0.001	excite rotations of molecules
10 μ m	0.1	excite vibrations of molecules
<0.4 μ m	>3.	photodissociation excite the electrons in the outer shells of atoms and molecules
0.1 μ m	10	ionize atoms or molecules
0.01 μ m	100	ionize inner shell electrons



Radiation Absorption (cont.)

Altitude at which various UV frequencies are absorbed from Chamberlain and Hunten

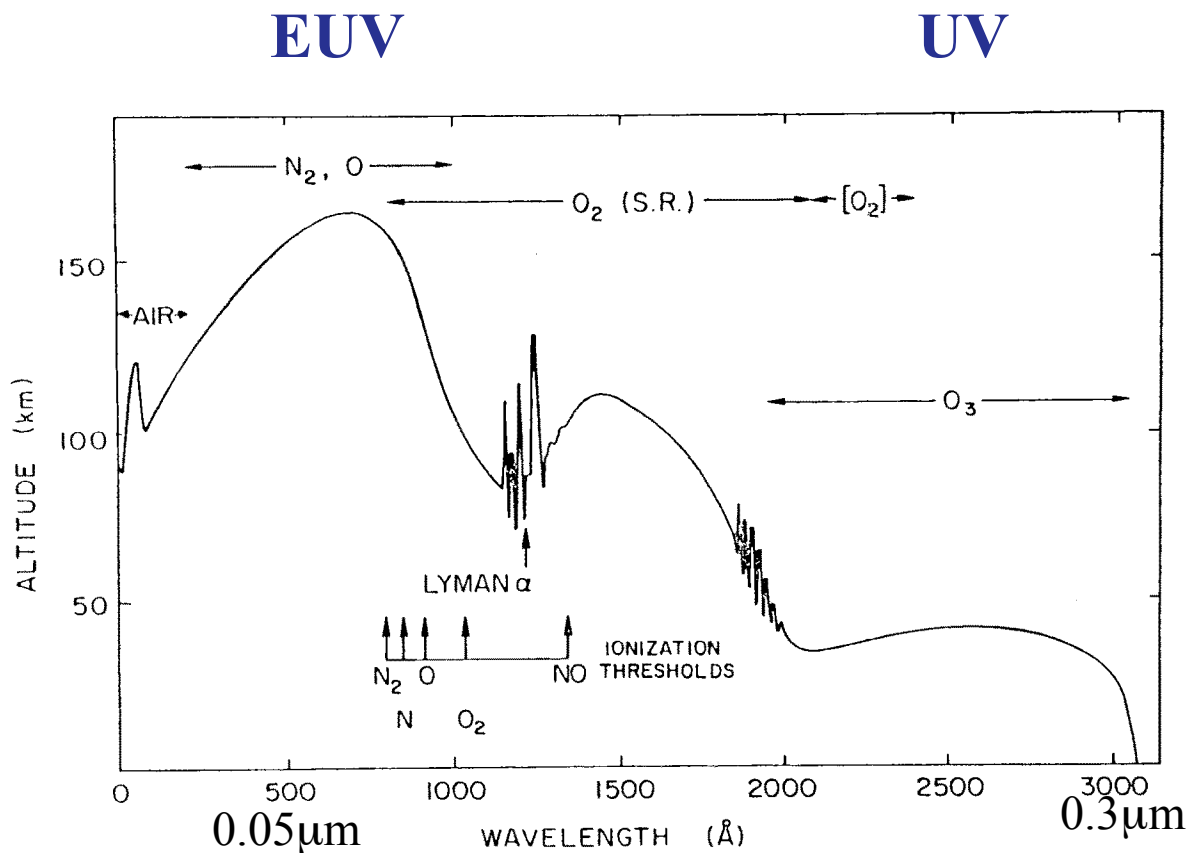


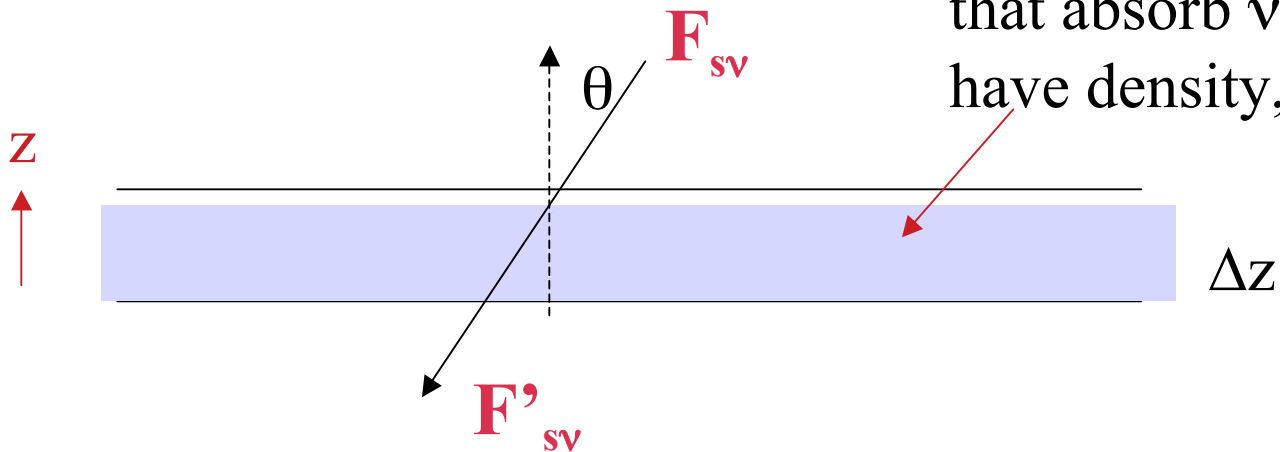
Fig. 1.8 Altitude at which the intensity of solar radiation drops to $1/e$ of its value outside Earth's atmosphere for vertical incidence. The Schumann–Runge and forbidden Herzberg O_2 absorbing regions are denoted by S.R. and $[O_2]$, respectively. [Based on data assembled in 1961 by P. J. NAWROCKI, K. WATANABE, and L. G. SMITH; adapted from L. HERZBERG (1965), in "Physics of the Earth's Upper Atmosphere," (C. O. Hines *et al.*, eds.) p. 40, Prentice-Hall, Englewood Cliffs, New Jersey.]

Note: EUV absorbed very efficiently

Radiation Absorption (cont.)

ABSORPTION of SUNLIGHT

Molecules that absorb ν have density, n_i



Δz is the layer thickness (positive up)

θ is the solar zenith angle

F_{sv} is the solar *energy* flux at frequency ν
 (when calculating T_e we used the *total*: F)

Change in flux in passing through Δz :

$$\Delta F_{sv} = F_{sv} - F'_{sv}$$

can you see that--

$$\Delta F_{sv} \propto n_i (\Delta z / \cos\theta) F_{sv}$$

(up is positive; n = number of absorbers/volume)

or
$$\Delta F_{sv} = \sigma_{abs} n_i (\Delta z / \cos\theta) F_{sv}$$

σ_{abs} = effective *cross section* of the absorber

$$\cos\theta \, dF_{sv} / dz = \sigma_{abs} n_i F_{sv}$$

Radiation Absorption (cont.)

Optical Path Length: τ

$$\cos\theta \, dF_{sv} / dz = \sigma_{abs} n_i F_{sv}$$

Rewrite

$$dF_{sv} / F_{sv} = \sigma_{abs} n_i dz / \cos\theta$$

Can solve using $n = n_0 \exp(-z/H)$.

But typically written as flux transmitted to altitude z :

$$F_{sv}(z) = F_{sv}(\infty) \exp[- \tau_v]$$

where $F_{sv}(\infty)$ is the solar at frequency ν onto the planet and τ is

$$\tau_\nu = \int_z^\infty \sigma_{abs} n_i dz / \cos\theta \sim \sigma_{abs} N_i(z) / \cos\theta$$

$\tau_\nu =$ optical path length for frequency ν

Thickness of atmosphere to radiation from outside: will depend on frequency, density of species absorb that

frequency with a cross section σ_{abs}

(should write $\sigma_{abs,\nu}$)

Light can also scatter (blue sky) so need to add $\sigma_{scat,\nu}$

$\{(n \sigma_{abs,\nu})$ often written as $(\rho k_{abs,\nu})$ ρ the mass density $\}$.

Radiation Absorption (cont.)

Heating by Absorption of Sunlight

Absorption in Atmosphere is a Source of Energy in the Heat Balance Equation

$$\text{Heating Rate/ Vol} = n_i \sigma_{\text{abs}} F_s(z) / \cos\theta$$

(Energy flux absorbed in Δz)/ Δz

Earlier we used dq as the change in energy of the gas per unit mass

$$\begin{aligned} \rho \, dq/dt &= \rho [c_v dT + p \, dV]/dt \\ &= \text{Energy absorption rate/ vol} \\ &\quad \text{at a given } z \text{ (fixed } p) \end{aligned}$$

Therefore, can rewrite at a fixed p :

$$\rho \, c_p \partial T / \partial t = n_i \sigma_{\text{abs}} F_s(z) / \cos\theta$$

Dropped subscript v in the above

What to sum over all frquencies absorbed

**Can also think of the Heating Rate =
Photon Flux x Photon Energy/($\lambda_{\text{ab}} \cos\theta$)**

λ_{abs} = mean free path for absorption

$1/\lambda_{\text{abs}}$ = density x cross section = $n_i \sigma_{\text{abs}}$

Chapman Layers

heating rate = $n \sigma F(z) / \cos\theta$
 (dropped subscripts)

Remember z dependence:

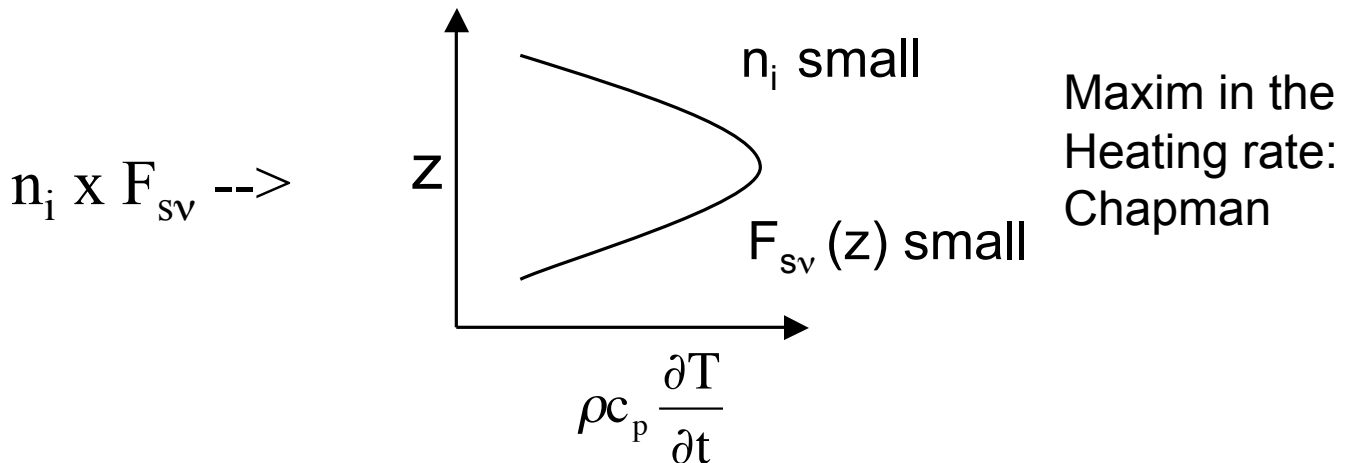
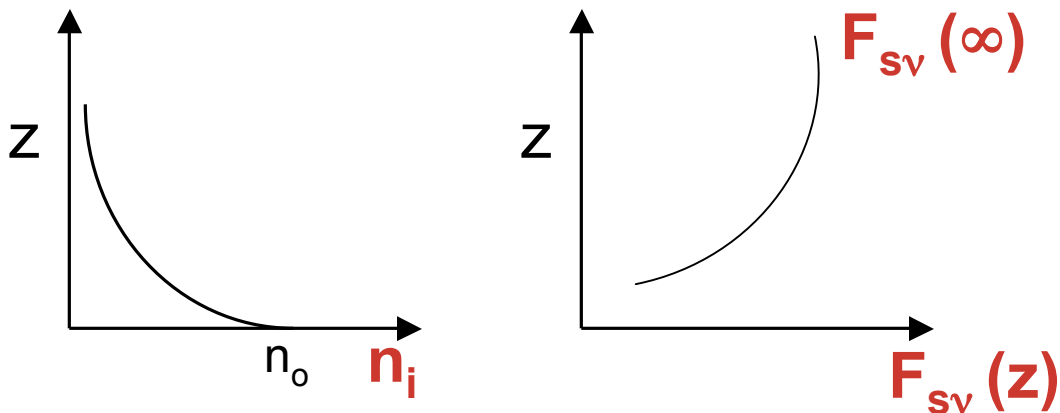
$$n(z) \approx n_0 \exp[-z/H]$$

$$F(z) = F(\infty) \exp[-\tau(z)]$$

$$\tau(z) = \int_z^\infty \sigma n dz / \cos\theta$$

$$\approx \sigma N / \cos\theta$$

$$\approx [H / \lambda_{\text{abs}} \cos\theta] \exp[-z/H]$$



Temperature Maxima -> Layered Atmospheres

Chapman Layers (cont.)

Find the Heating Maximum (dropped subscripts)

$$n = n_0 \exp \left[-\int_0^z \frac{dz}{H} \right] \approx n_0 \exp [-z/H]$$

$$F = F(\infty) \exp[-\tau]$$

$$\tau \approx \sigma N(z) / \cos \theta; \quad \text{with } N \approx H n(z)$$

where $N(z)$ is column density of absorbing species

$$\begin{aligned} \text{HeatingRate} &\propto \frac{\partial T}{\partial t} \propto n(z)F(z) \\ &\propto n(z) \exp[-\sigma N(z) / \cos \theta] \end{aligned}$$

To find altitude for maximum heating

$$\frac{d}{dz} nF = 0$$

Show max. occurs when: $n_{\max} = (H \sigma)^{-1}$

or

$$\underline{\underline{N_{\max} = \sigma^{-1}}}$$

$$\text{UV} \quad \sigma \rightarrow \sigma_{\text{abs}} \approx 10^{-17} - 10^{-19} \text{ cm}^2$$

**The column where absorption is a max is
The inverse of the absorption cross section**

Chapman Layers (cont.)

Altitude for Maximum Heating Rate

The maximum heating rate by absorption of sunlight in the atmosphere occurs

$$\text{when } N_{\max} \approx \sigma_{\text{abs}}^{-1}$$

More precisely : only certain species absorb

Therefore $N_{i,\max}$ is really the column of absorbing species that the incident sunlight passes through :

$$c_i N_{\max} \approx \sigma_{\text{abs}}^{-1}$$

if c_i is the concentration of absorbers
and N is all of the atmosphere

Again :

$$\begin{aligned} \sigma_{\text{abs}} &\sim \text{Prob.} \times \text{size of molecule (} r \sim 3\text{\AA)} \\ &\sim \text{Prob.} \times 10^{-15} \text{ cm}^2 \end{aligned}$$

Probability of absorbing \sim radius/ wavelength
 $\sim 10^{-2} - 10^{-3}$ in UV

$$\text{Or } \sigma_{\text{abs}} \sim 10^{-17} - 10^{-19} \text{ cm}^2$$

If molecules can absorb readily

Therefore, a column of absorbers : $\sim 10^{17} - 10^{19}$ (molecules/cm²)

Total on Earth $> 10^{23}$ molecules/cm²

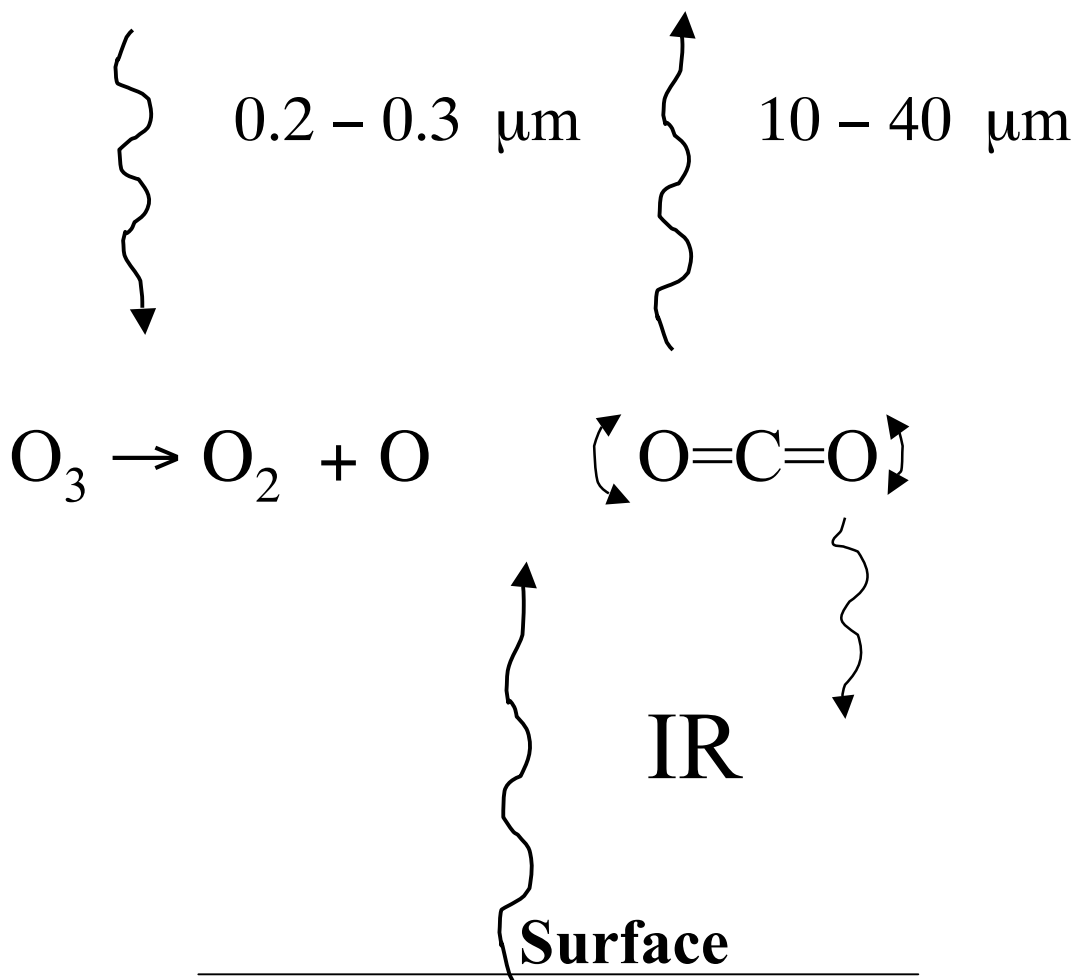
so only a small fraction can do it!

**Only part way there; this is only the heating
Not the T vz. z yet!**

Ozone Formation

What Occurs Near Stratopause (~ 50 km)

Near UV light absorbed in atmosphere primarily by O_3
Surface is heated by the visible and cooled by the IR
But the IR does not go straight to space, some of it is absorbed
by CO_2 , H_2O , etc. It must then be re-emitted.



**Before considering heat balance
Need O_3 formation!**

Ozone Formation (cont.)

Remember O_2 absorbs at
Longer wavelengths than N_2

See slide 13

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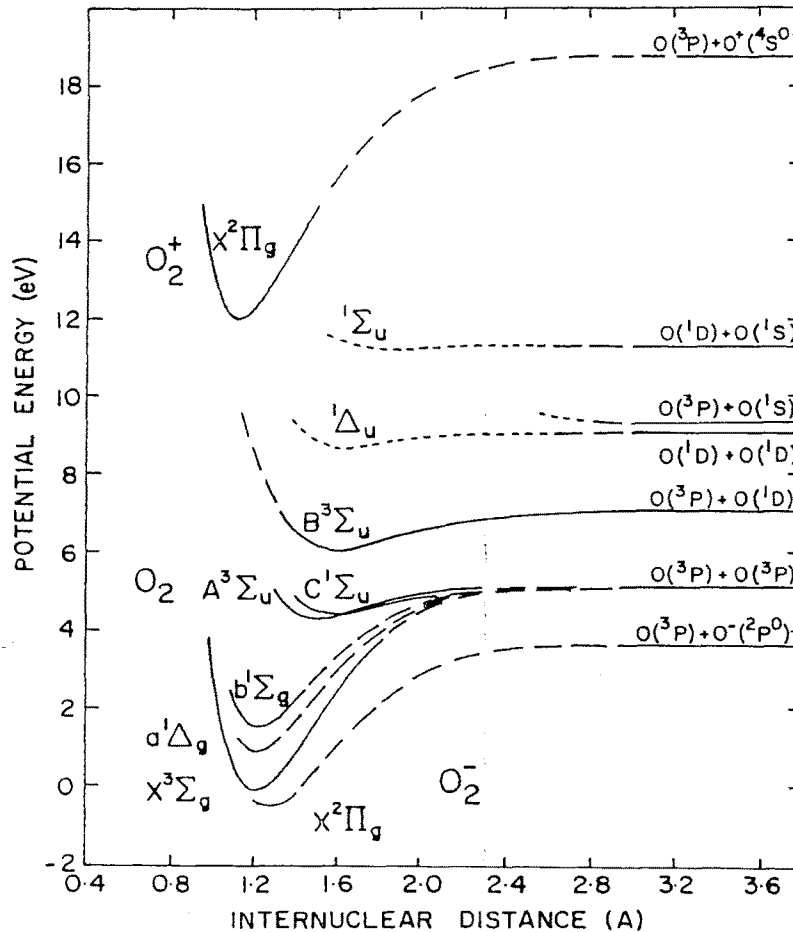
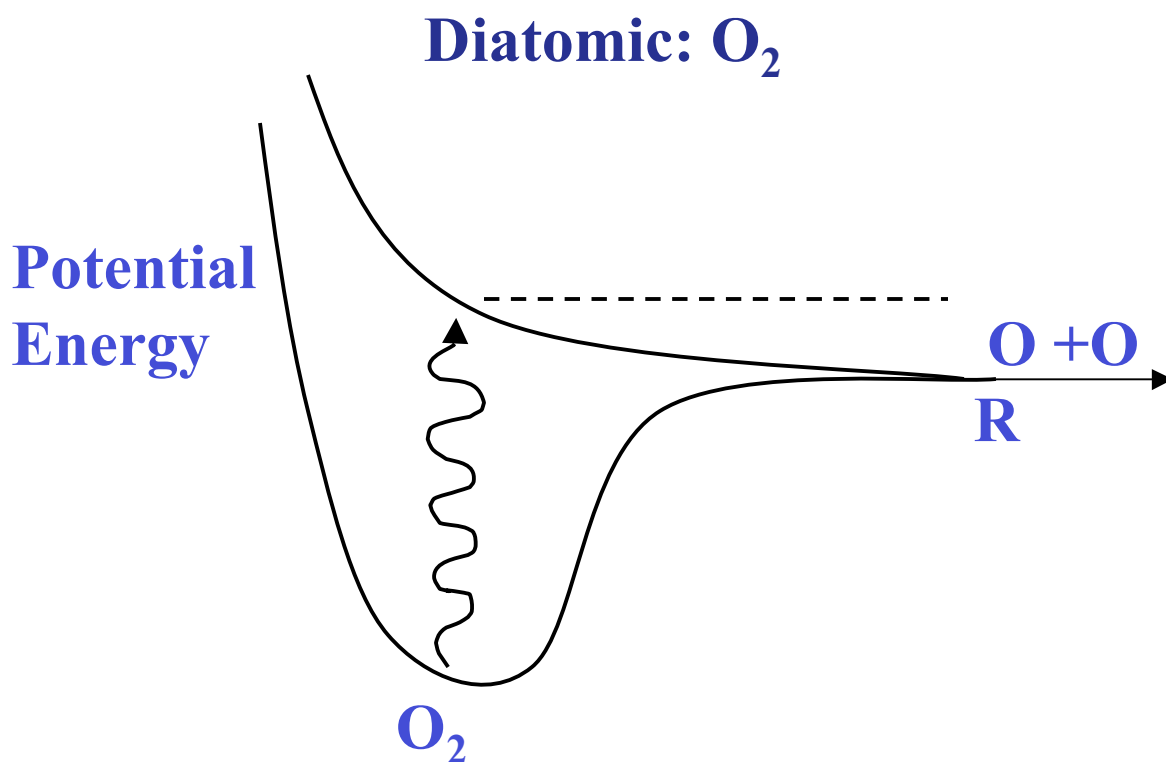


Fig. 1.9 Simplified potential energy diagram for oxygen. Along the right side are listed the dissociation products; an energy level diagram of O appears as Fig. 6.3.

Some Oxygen Molecule Energy Curves

Ozone Formation (cont.)

Photoabsorption in a Molecule



**Two states shown: Ground Attractive
and a higher state: here repulsive
Photon energy greater than energy
to dissociate**

**Vibrations slow-- Transition is at a fixed R
(Franck-Condon Principle)**

Ozone Formation (cont.)

- Ozone formation



(EUV starts process)



(why M?)

- How is O_3 destroyed?



**This is the UV radiation that
Heats near the stratopause and
Causes skin cancer!**

Absorption of UV photon Destroys O_3

Ozone Formation (cont.)



Large absorption cross section
mixing ratio: ~ 0.3 ppm

but only absorber at $0.23\text{--}0.29\ \mu\text{m}$

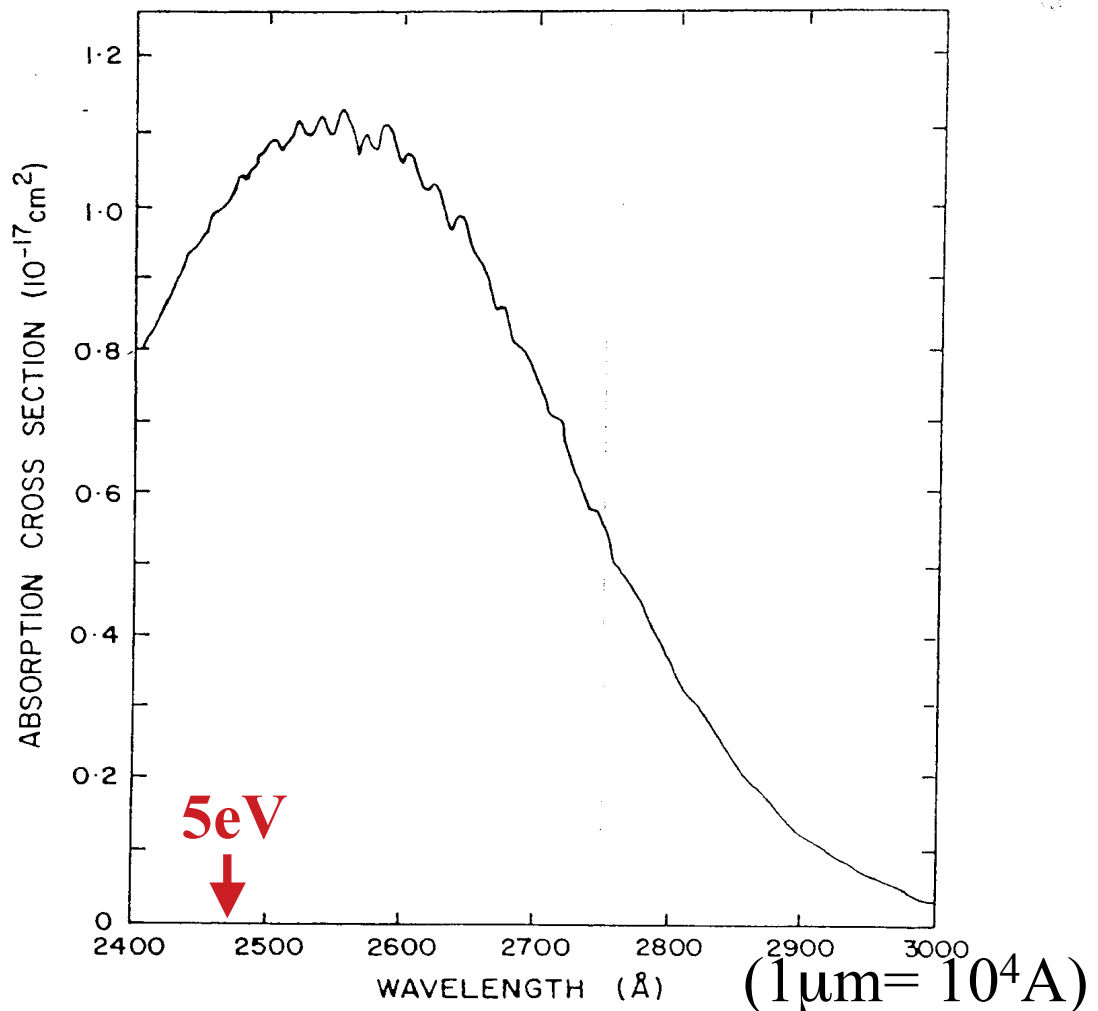


Fig. 1.7 Absorption cross sections of the Hartley bands and continuum. [Measurements by E. C. Y. INN and TANAKA, (1953), *J. Opt. Soc. Amer.* 43, 870.]

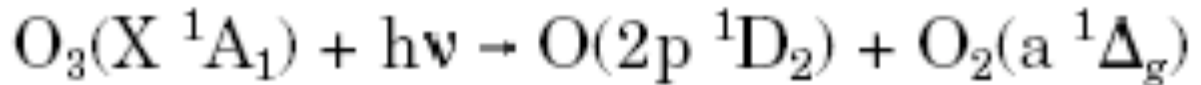
Dissociation energy 1.05 eV

Atmospheric 'thickness' of O_3 is $\sim 0.3\text{cm}$ at STP:

$$\tau\{250\text{nm}\} = 10^{-17}\text{cm}^2 \times 0.3\text{cm} \times 2.7 \times 10^{19}/\text{cc} = 81$$

Ozone Formation (cont.)

Hartley Band: allowed transitions



Chappius Band: 'forbidden' transitions

Much smaller cross section

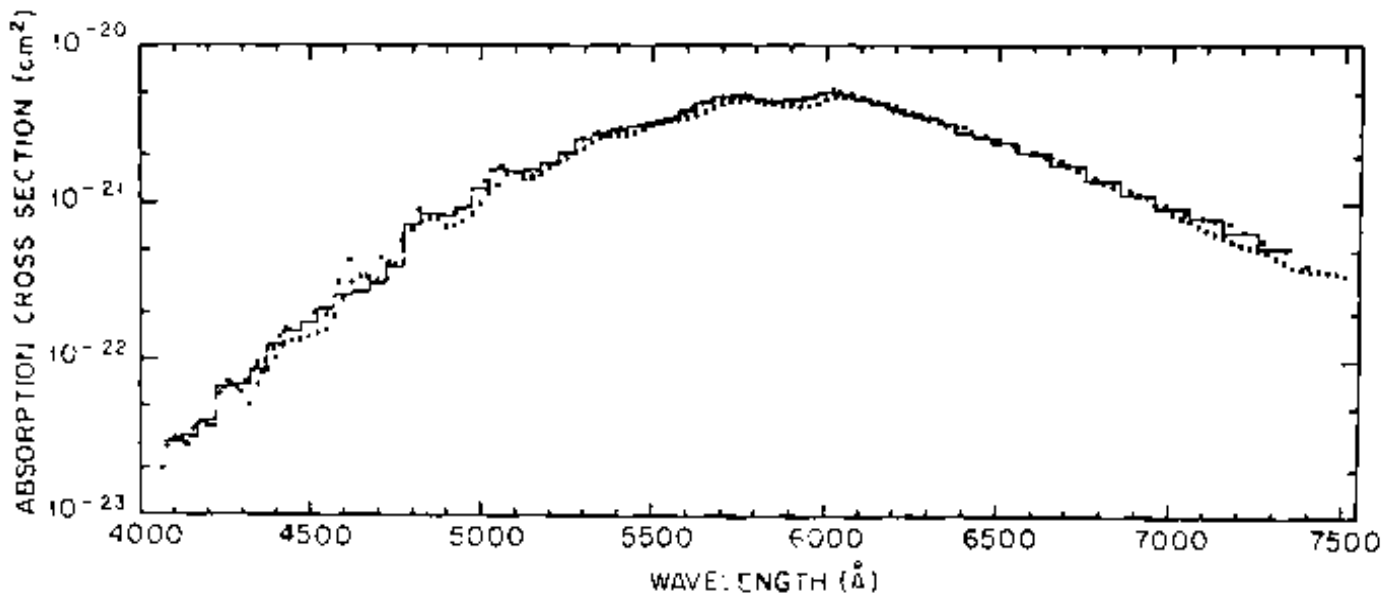
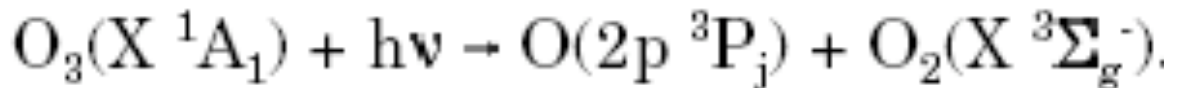


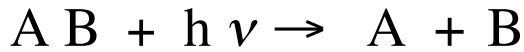
Fig. I-20. Absorption cross section of ozone versus wavelength in the Chappuis bands. Data key as in Fig. I-19. From Ackerman (1971) with permission of Reidel Publ. Co.

Chapman Equations

Chemistry Review: Rate Equations

Reaction and Photoabsorption Coefficients

Photodissociation



$$\frac{dn_{AB}}{dt} = - J n_{AB}$$

n_{AB} = density of molecule AB

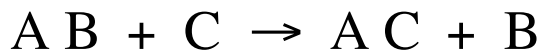
J = absorption cross section x photon flux \rightarrow 1 / time

$$= \sigma_{\text{abs}} F_{\text{sv}} / h\nu ; F_{\text{sv}} \text{ is the photo - energy flux at } \nu$$

[need to average over photon frequencies, ν , and atmos. comp.]

J^{-1} is average lifetime of AB in the solar flux

For a reaction



$$\frac{dn_{AB}}{dt} = - k n_{AB} n_C$$

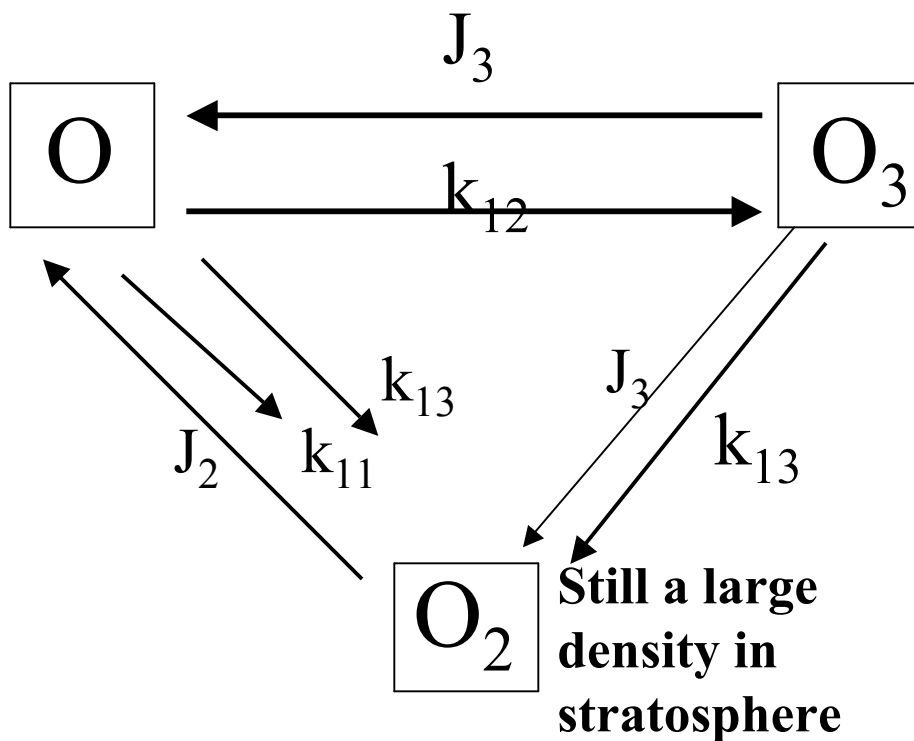
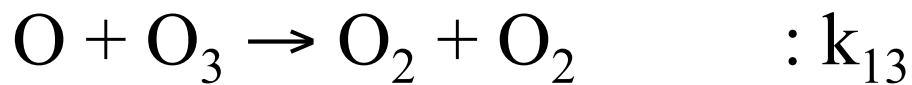
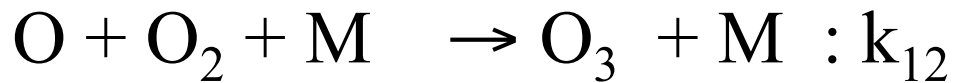
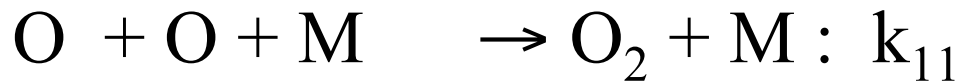
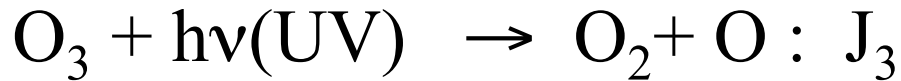
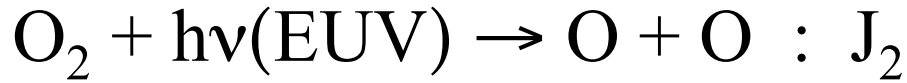
k = effect area x speed = $\sigma_R v$ = volume / time

(reaction rate for two bodies: AB and C)

Typically k is averaged over a thermal distribution of speeds v and σ_R depends on v

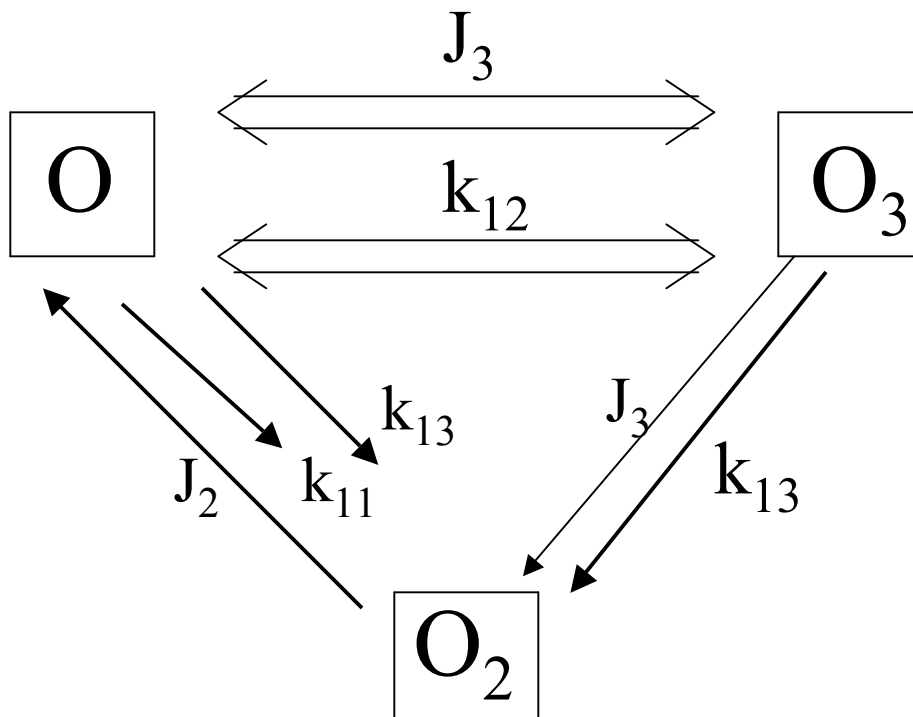
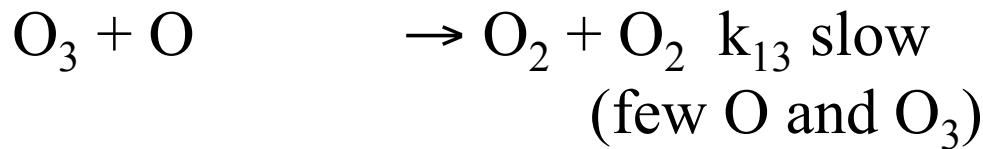
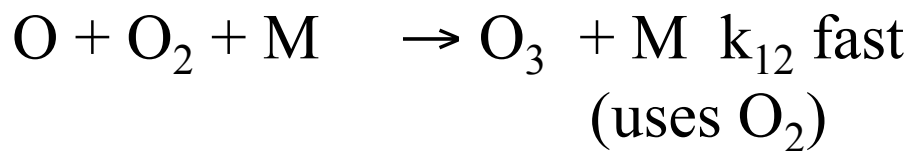
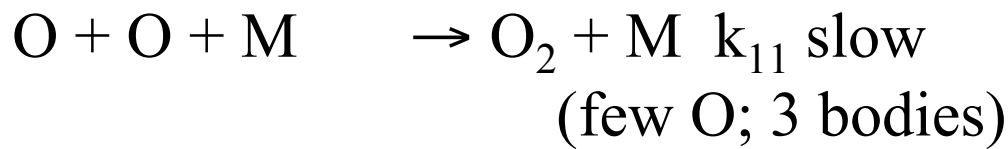
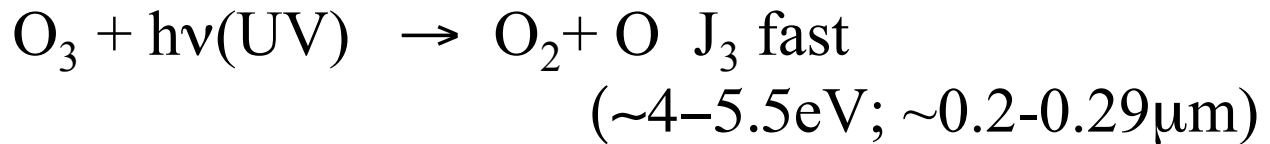
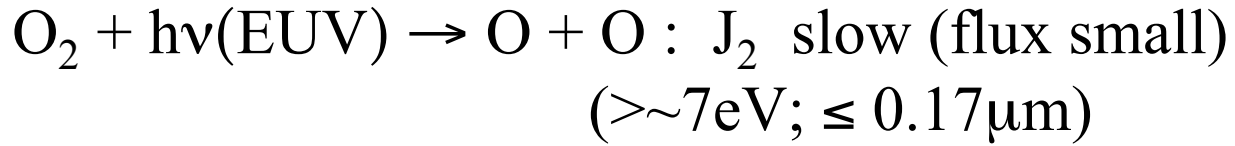
so write $k_{AB + C \rightarrow A + BC}(T)$ or $k_i(T)$

Chapman Equations (cont.) Formation and destruction of Ozone



Chapman Equations (cont.)

Formation and destruction of Ozone



Chapman Equations (cont)

Densities of O_2 , O_3 and O we need to calculate

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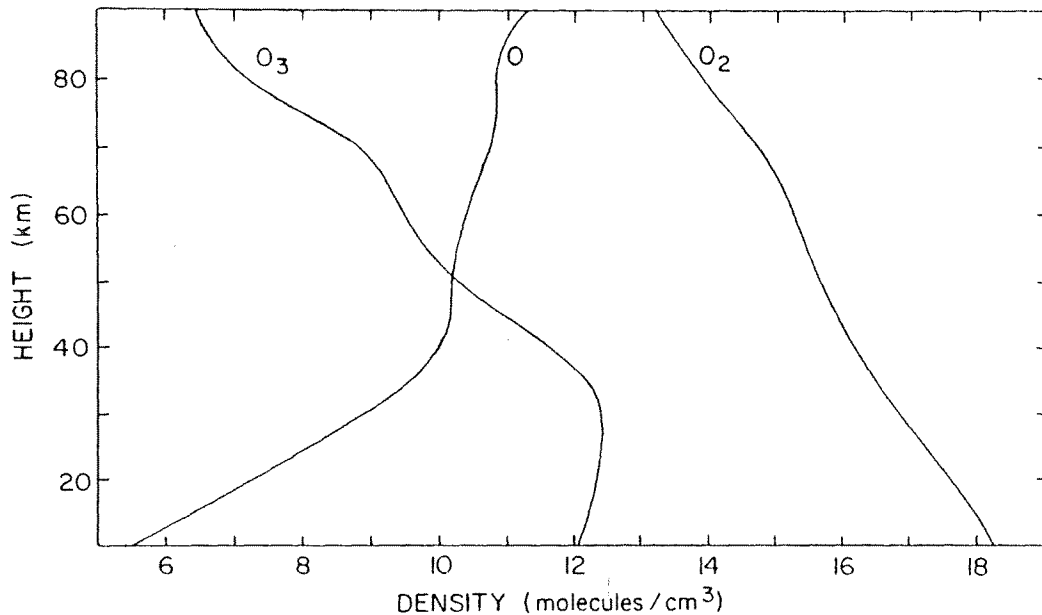


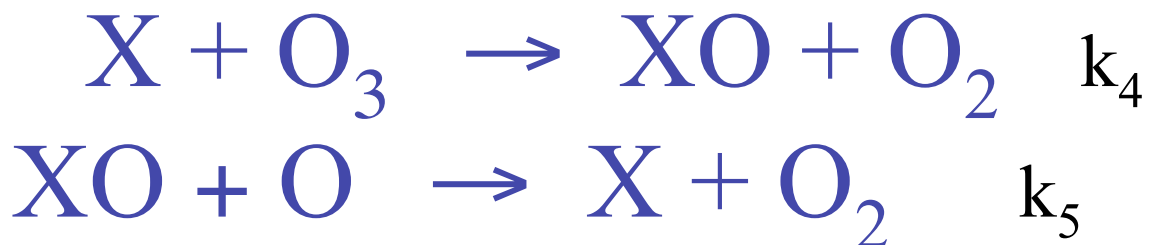
Fig. 1.10 Daytime equilibrium of oxygen allotropes according to the Chapman theory. The abscissa is $\log_{10} N$. [Calculations by D. R. BATES (1954) in "The Earth as a Planet," (G. P. Kuiper, ed.), p. 581, Univ. Chicago Press, Chicago.]

**Note: Peak in ozone density
is not the heating peak at
the stratopause: ~50km**

Chapman Equations (cont.)

Another O₃ Destruction Process

Reactive Species
that are recycled



Equivalent to



Nitrous Oxides: $N_2O \rightarrow N + NO$

Fertilizers, Sewage, Lightning, Aurora etc.

Chlorine: ClO_x, Cl_x

Volcanoes (HCl); Chloroflourocrabons
($CFCl_3, CF_2CL_2$)

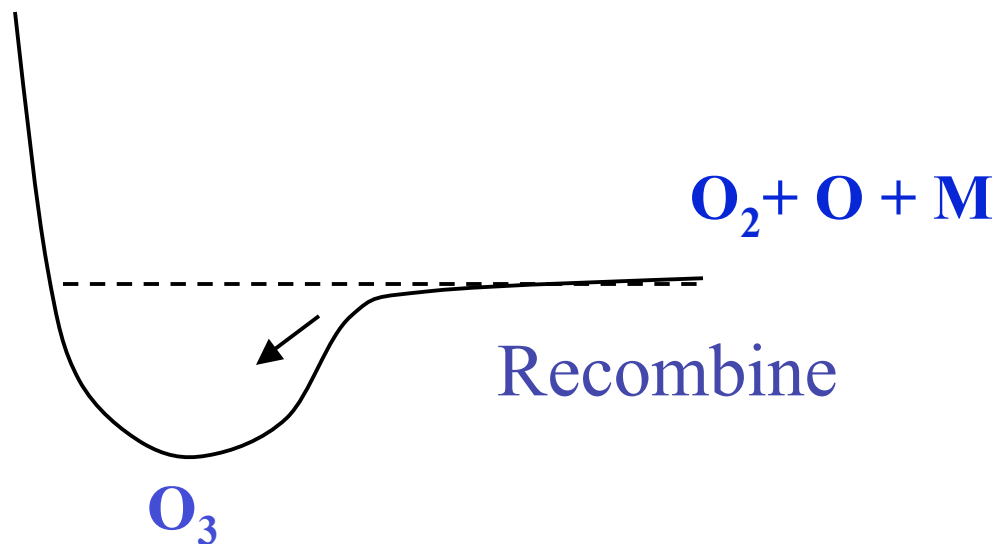
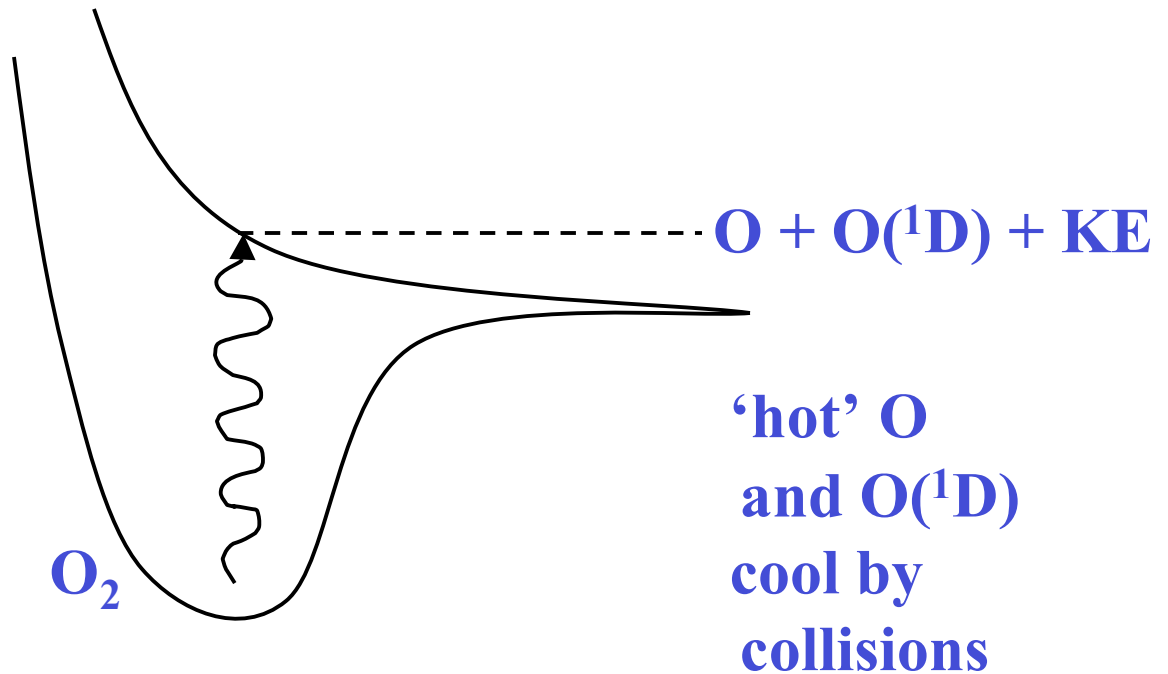
Ice clouds (Noctalucent Clouds $\rightarrow H$)



Stratospheric Heating

The above does not say anything about how heat gets in; only how O_3 is formed and lost

How Does Heat Get In ?



Formed vibrationally hot: cools by collisions

Stratospheric Heating (cont)

SUMMARY

Ozone Heating in Upper Atmosphere forms the stratosphere



Destroy O_3 :

Photo Absorption in



Also

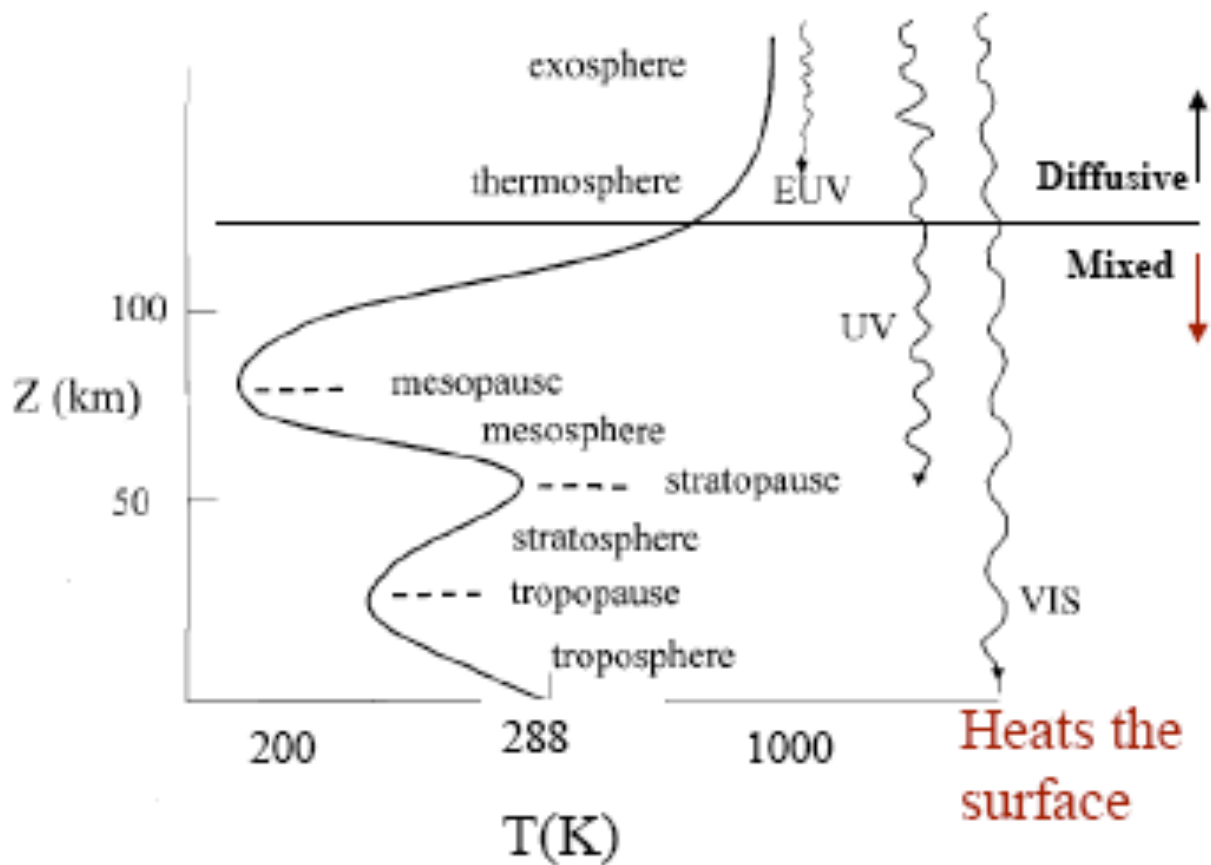


Cooling: CO_2 Radiation in IR ($\sim 15\mu\text{m}$)
(not much gaseous H_2O in stratosphere)
(have not done the cooling yet)

Temperature vs. Altitude

Earth's Atmosphere is *Layered*

Radiation Absorption Indicated



Remember: we still only have dT/dt the heating rate

Need cooling!

#2 Summary

Things you should know

Tropospheres

Absorption of Radiation

Optical Path Length

Photo-absorption Cross Section

Chapman Layer

Reactions Rates

Ozone Equations

Stratospheric Heating