Ionospheres of the Terrestrial Planets

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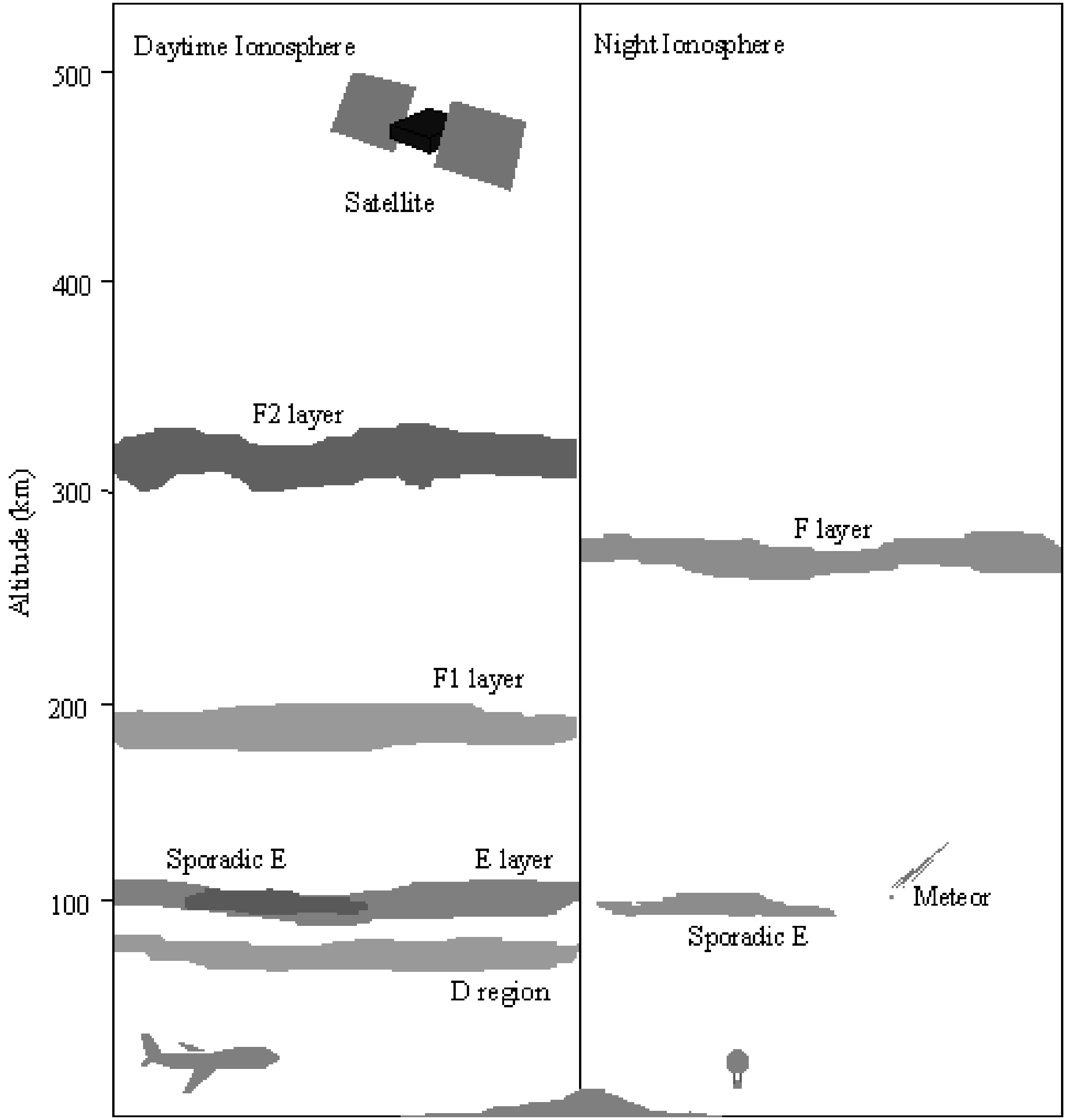
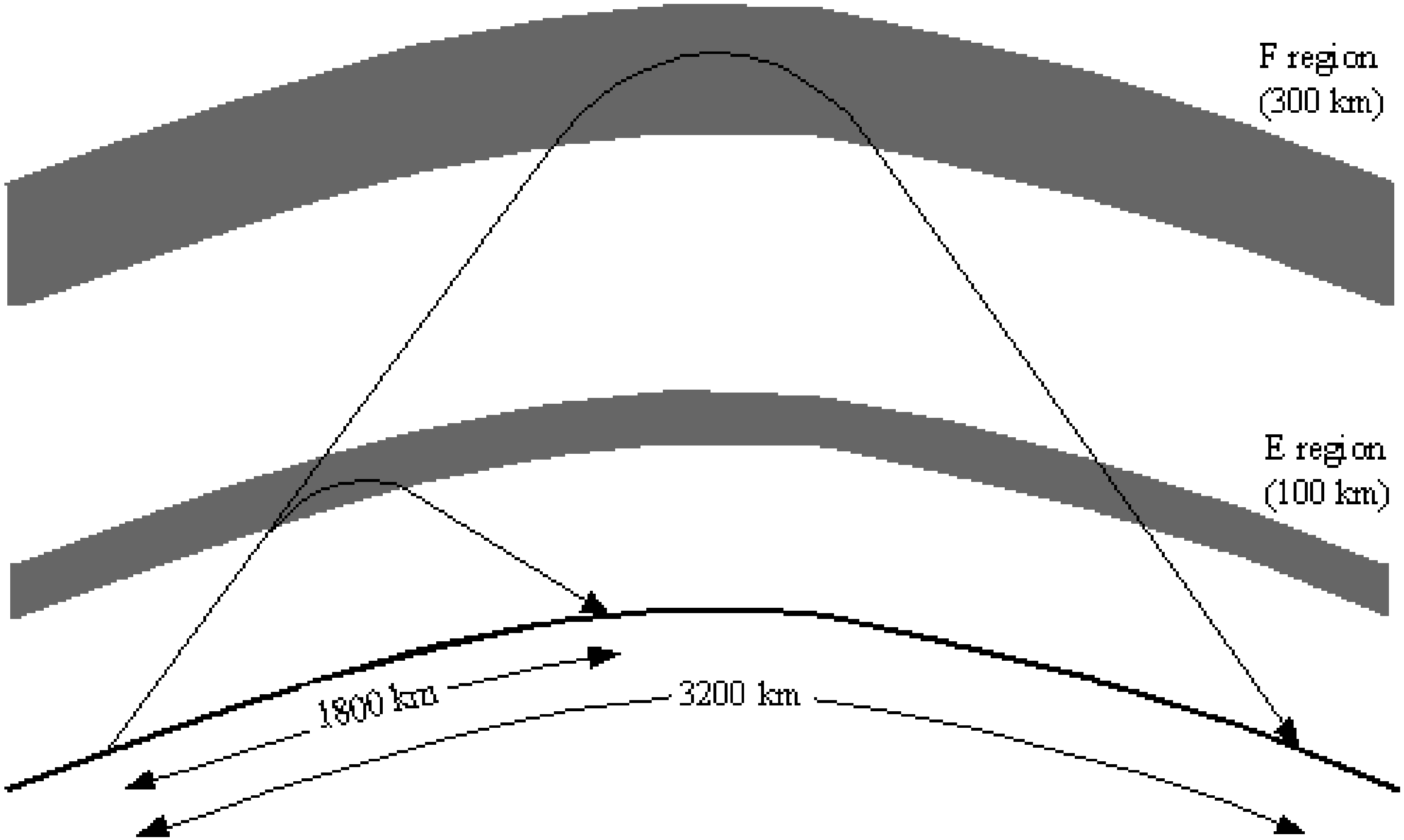
Outline

- Introduction to Earth's ionosphere
- Overview of Earth's atmosphere
- Ionization processes
- Chemical processes
- Mars & Venus
- Why is Earth so different?

“Layers” in Earth’s Ionosphere



Reflection of Radio Waves by the Ionosphere

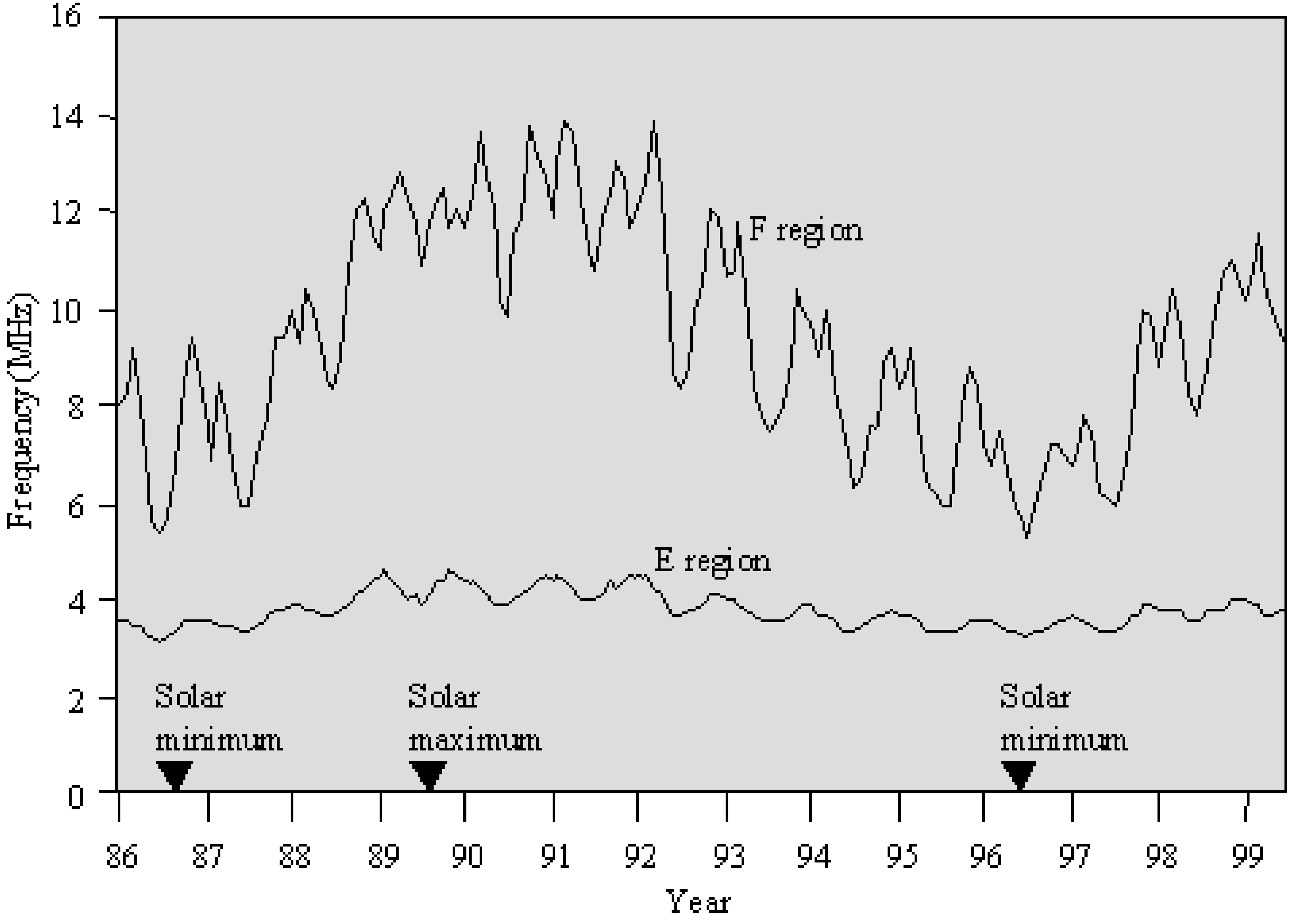


Reflection starts at the "Critical Frequency", which is when the radio frequency equals the plasma frequency.

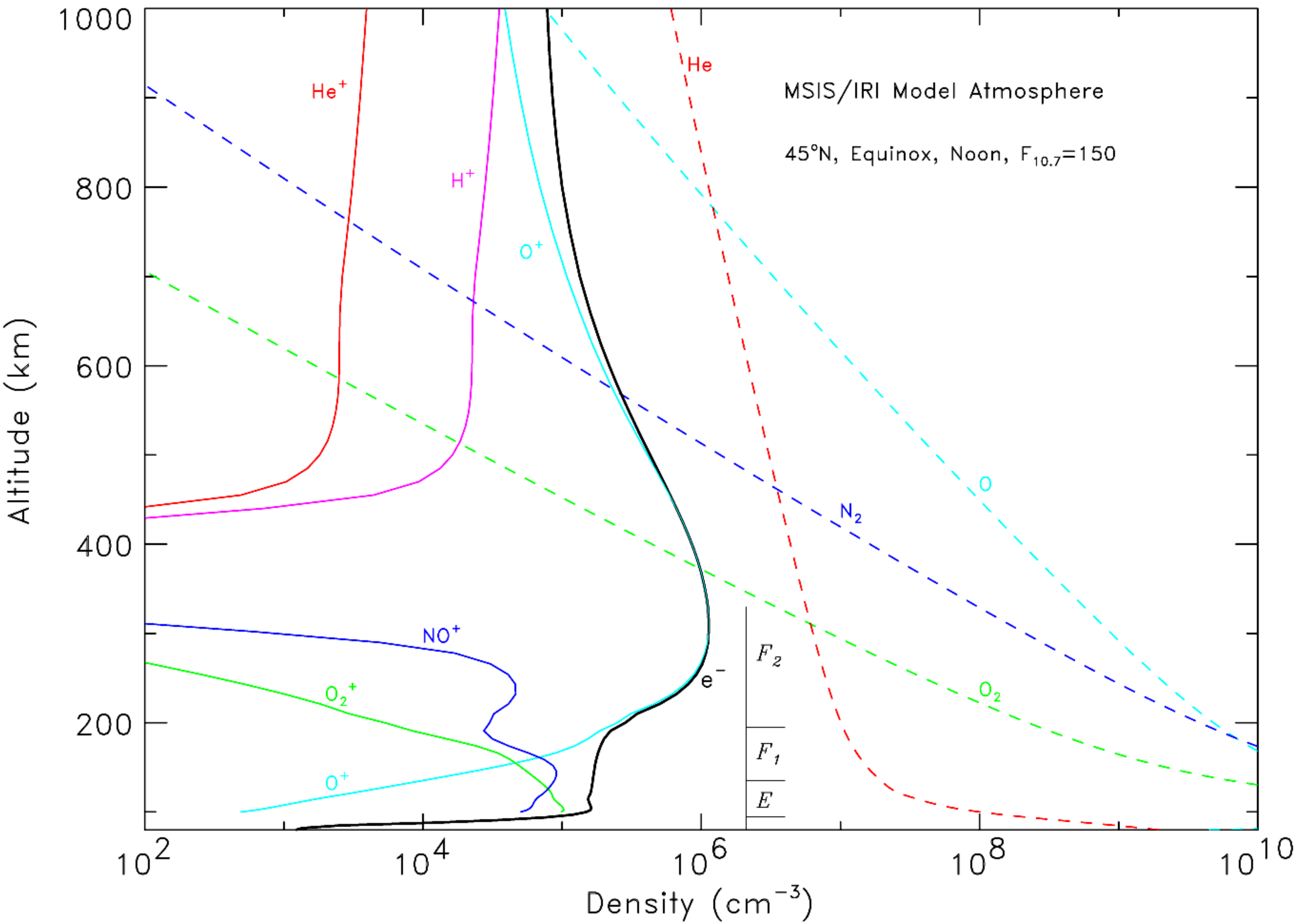
$$f_0 = 9\sqrt{10^{-6} n_e}$$

(f_0 in megahertz, n_e in cm^{-3})

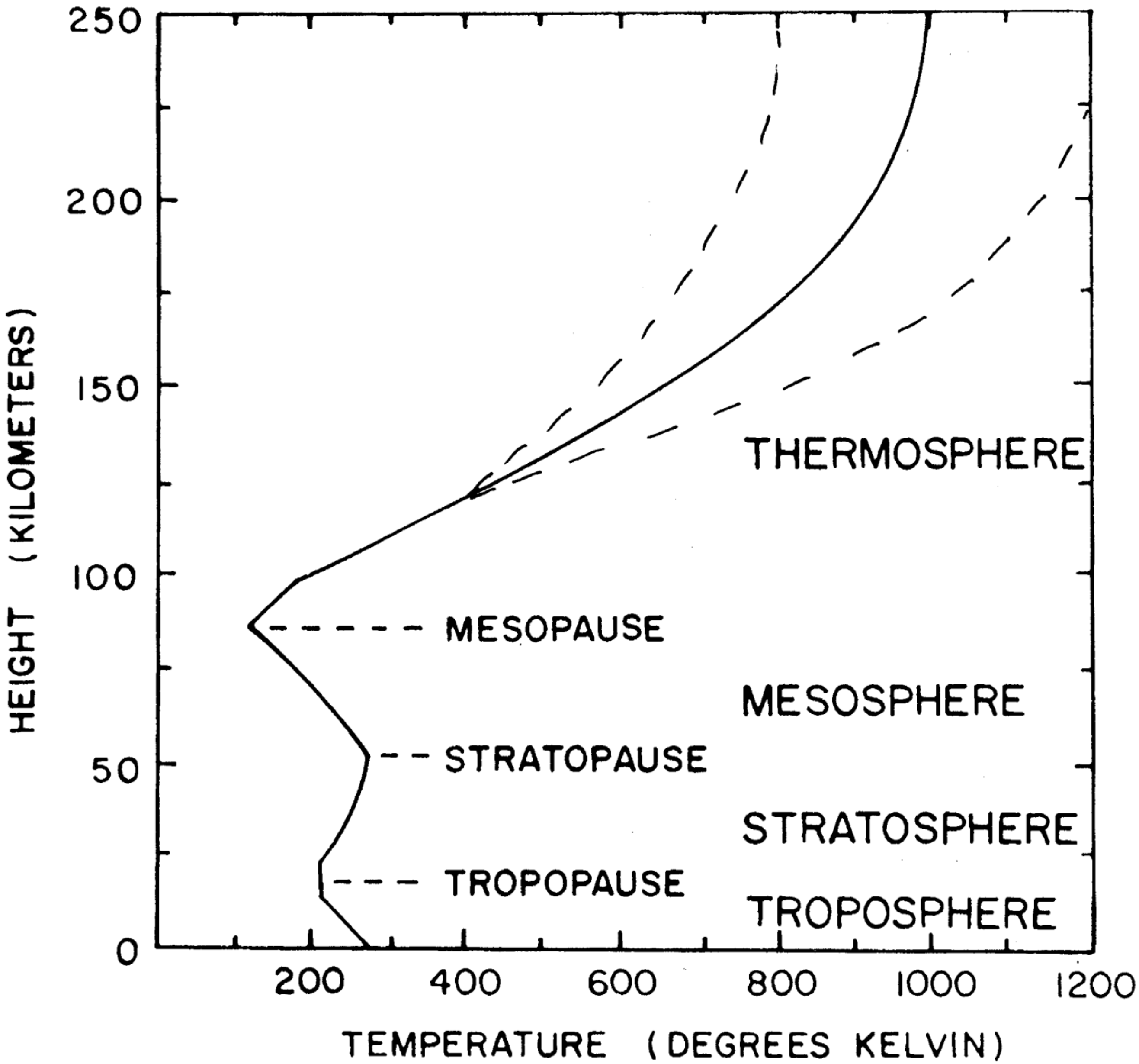
Critical Frequency Varies with Season and Solar Cycle



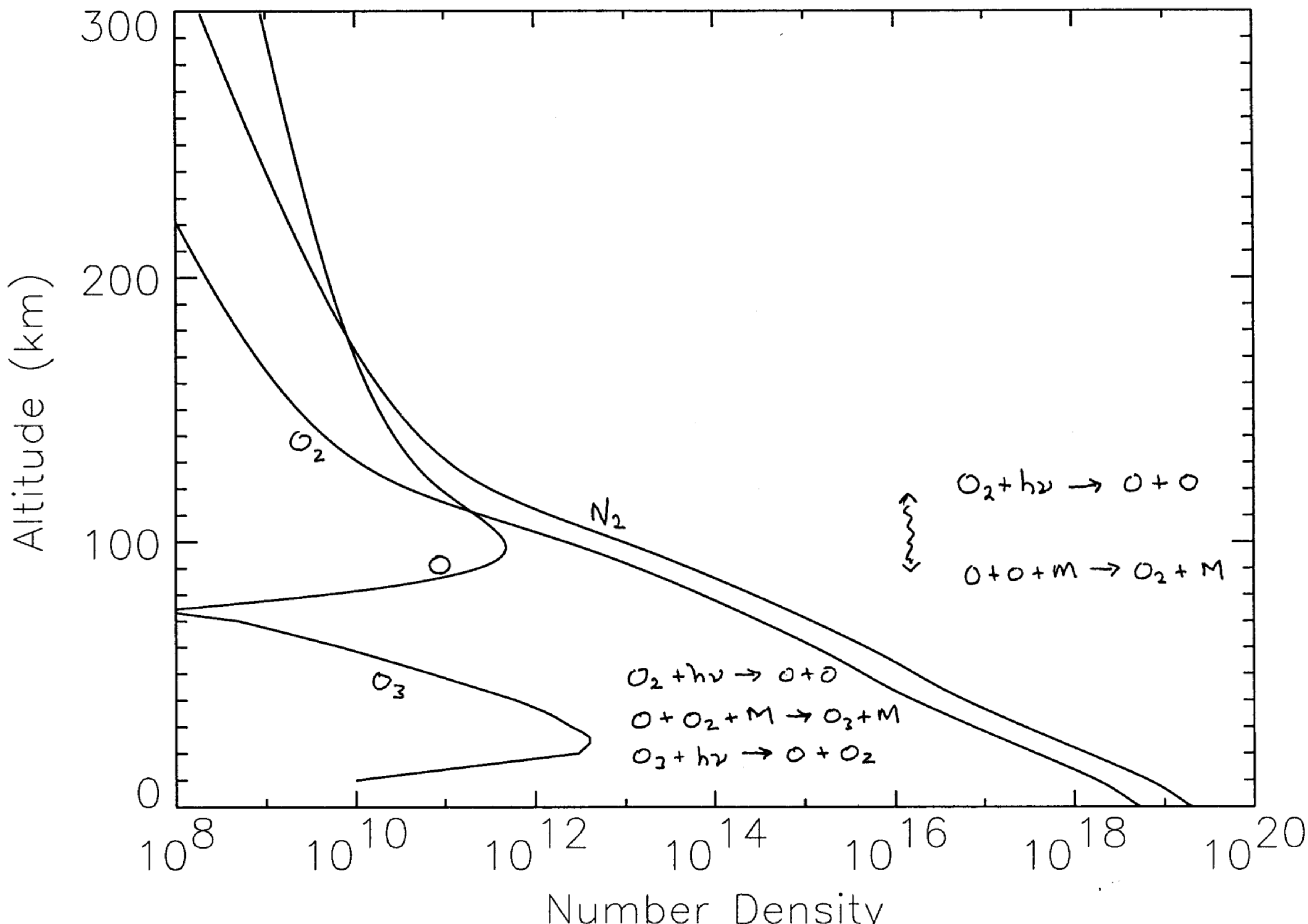
The Ionsphere is Mostly Neutral



Thermal Structure of Earth's Atmosphere



Density Structure of the Earth's Atmosphere



Atmospheric Distribution in Hydrostatic Equilibrium

Good text: Chamberlain & Hunten, Theory of Planetary Atmospheres

Pressure Gradient: $$\frac{dp}{dz} = -g(z)\rho$$

height derivative of pressure equals acceleration of gravity times density

Perfect Gas Law: $$p = nkT = \frac{\rho}{M}kT$$

Approximation: If g and T are not functions of z, then:

$$\frac{dp}{dz} = -p\frac{Mg}{kT} = -\frac{p}{H} \qquad H = \frac{kT}{Mg}$$

H = scale height (e-folding distance)

$$\frac{dp}{p} = -\frac{dz}{H} \qquad p(z) = p(z_0)\exp\left[-\frac{z - z_0}{H}\right]$$

Atmospheric Density Distribution

If T, M, and g are not functions of z:

$$n(z) = n(z_0)\exp\left[-\frac{z - z_0}{H}\right]$$

Mixed atmosphere (below ~100 km):

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

M is the mean molecular weight of atmospheric gases

Diffusively separating atmosphere (above ~100 km):

$$H_i = \frac{kT}{m_i g}$$

m_i is the molecular weight of individual species

— *Each species follows its own scale height.*

Column Density

Column Density: the number of molecules per unit area in a column above z_0:

$$N(z_0) = \int_{z_0}^{\infty} n(z)dz$$

Approximation for constant *H*:

$$N(z_0) = \int_{z_0}^{\infty} n(z_0)\exp\left[-\frac{z-z_0}{H}\right]dz = -Hn(z_0)\ \Big|_{z_0}^{\infty} \exp\left[-\frac{z-z_0}{H}\right]$$

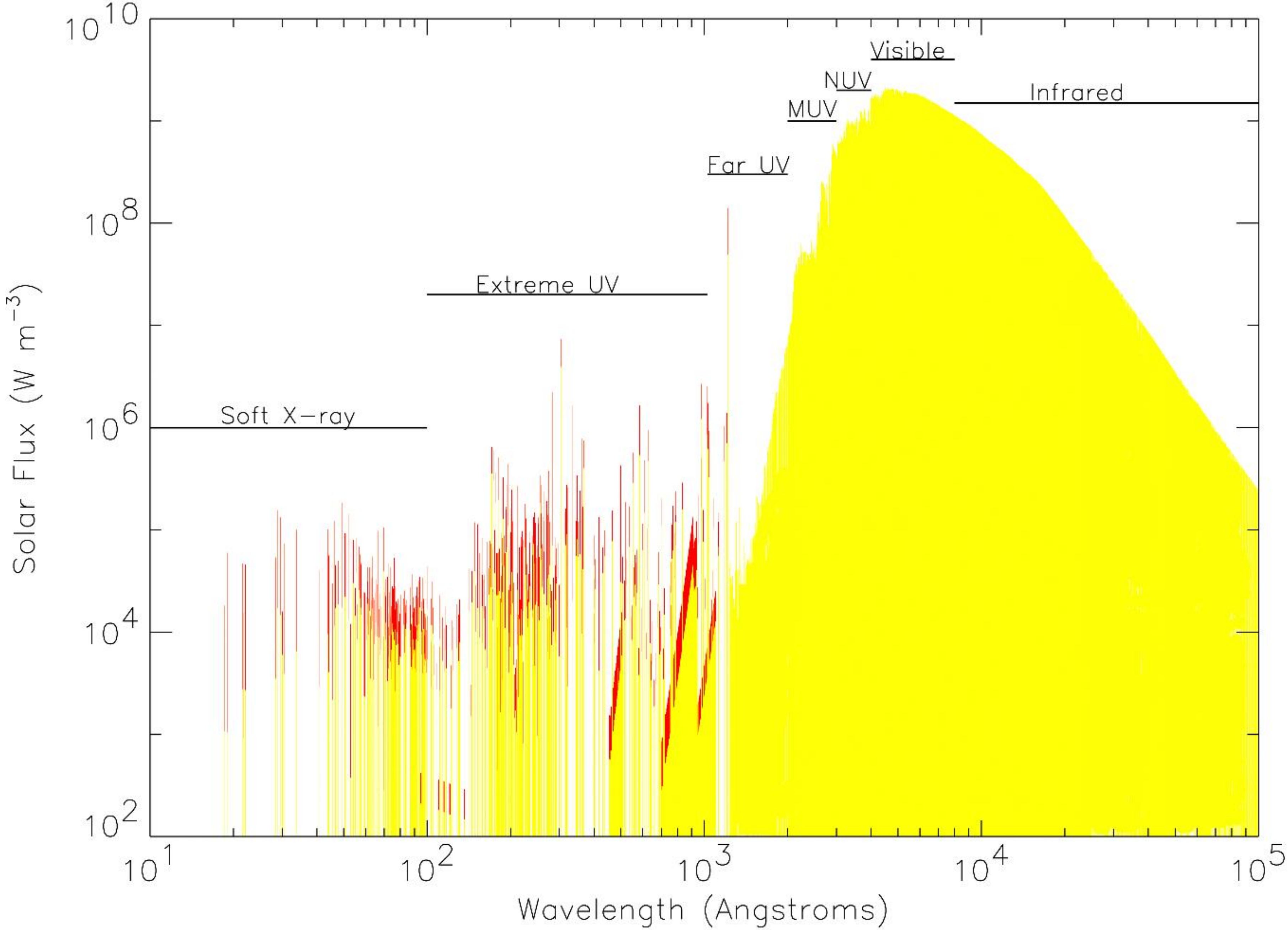
$$N(z_0) = Hn(z_0)$$

Question for Discussion

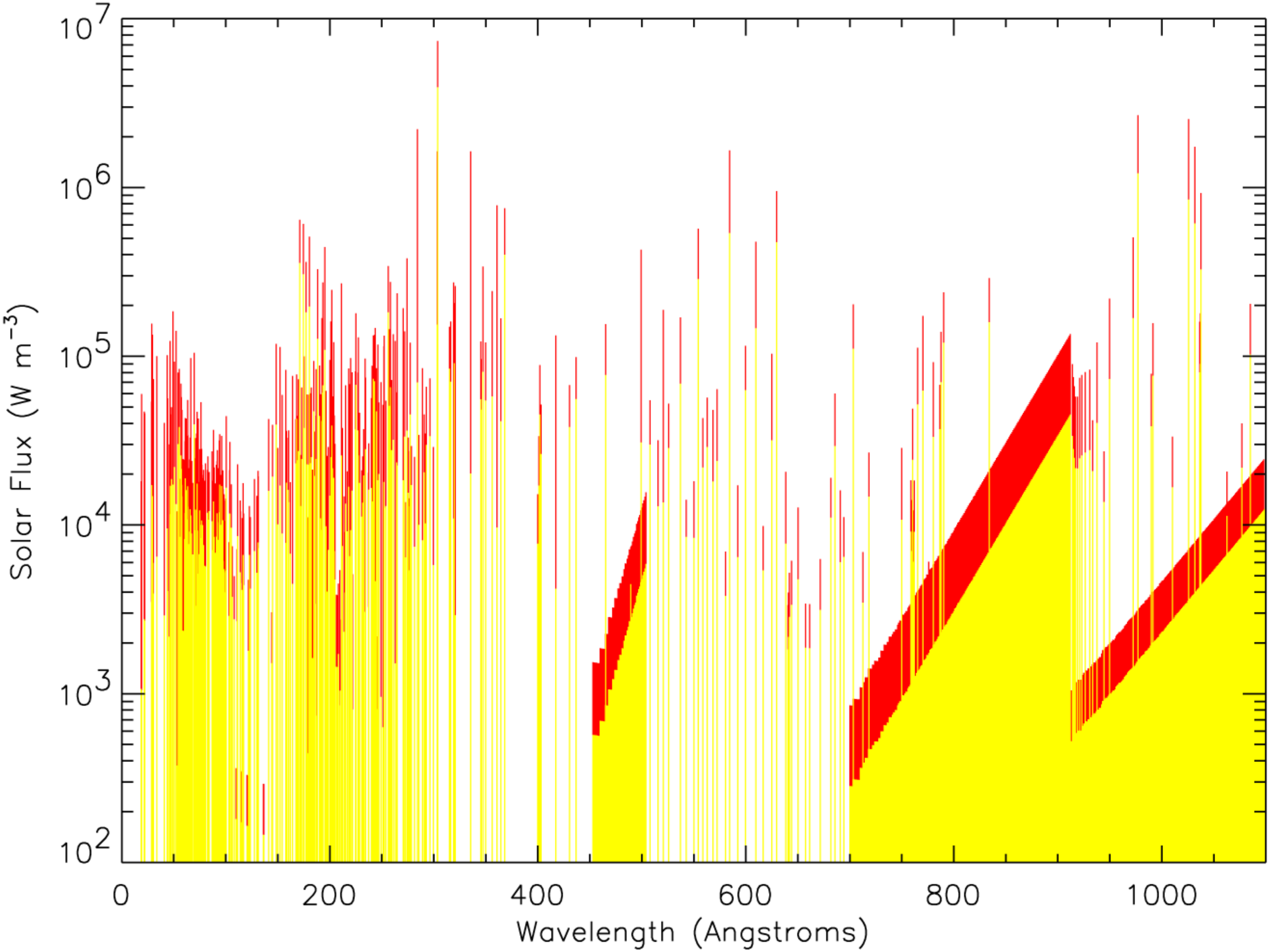
Suppose that a satellite is in low-Earth orbit at 300 km altitude. If the temperature of the thermosphere increases (for instance, as a result of an increase in solar ultraviolet radiation) then the density at 300 km will:

1. Increase
2. Decrease

The Solar Spectrum



Solar Extreme-Ultraviolet and Soft X-ray Spectrum



Where does ionization occur in an atmosphere?

Controlled by *cross sections* of atmospheric gases for absorption (σ) and ionization (σ_i).

Which are in general a function of wavelength (λ).

For a single-species, plane-parallel atmosphere, at any particular λ:

Ionization Rate = (radiation intensity) x (ionization cross section) x (density)

$$q(z) = q_z = I_z \sigma_i n_z$$

$$n_z = n_0 \exp\left[-\frac{z - z_0}{H}\right]$$

Beer's law: $$I_z = I_\infty \exp(-\tau_z)$$

where τ_z is the *optical depth*: $$\tau_z = \frac{\sigma N_z}{\mu} = \frac{\sigma n_z H}{\mu} = \frac{\sigma n_0 H}{\mu} \exp\left[-\frac{z - z_0}{H}\right]$$

and μ = cos (*solar zenith angle*)

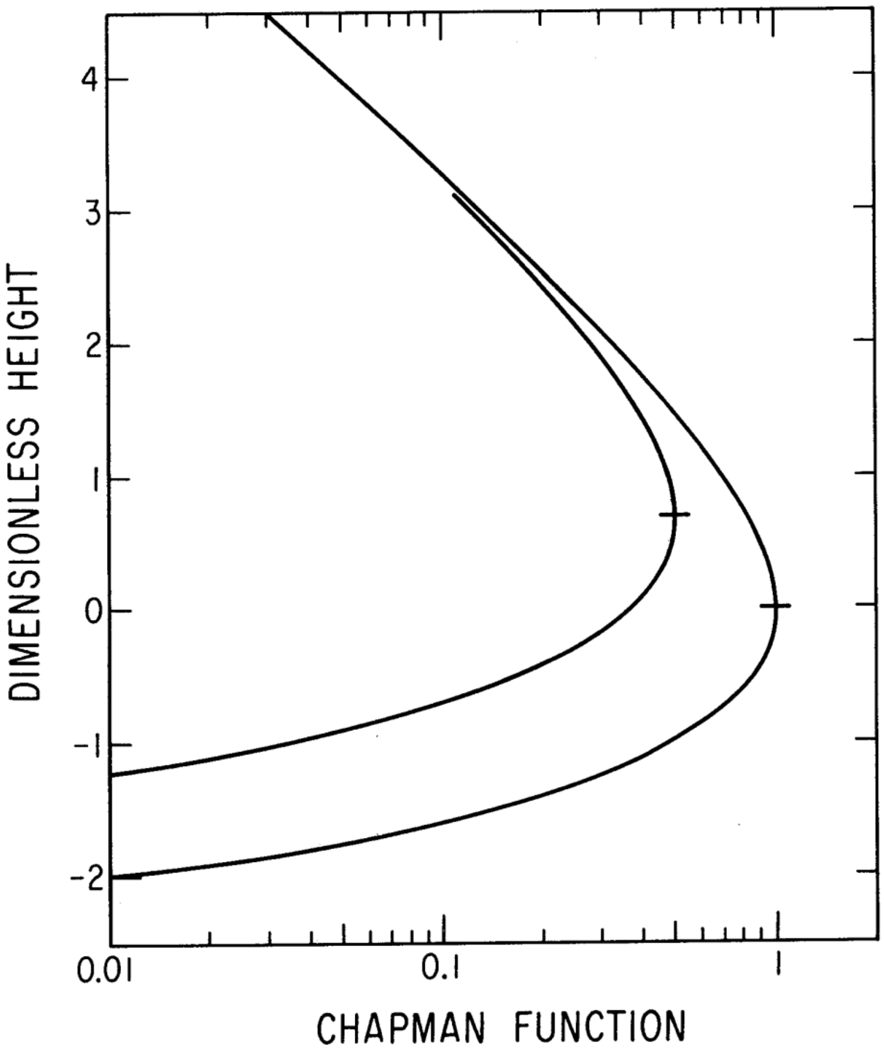
$$I_z = I_\infty \exp\left[-\frac{\sigma n_0 H}{\mu} \exp\left(-\frac{z - z_0}{H}\right)\right]$$

Chapman Function

$$q_z = I_z \sigma_i n_z$$

$$q_z = I_\infty \exp(-\tau_z) \sigma_i n_0 \exp\left[-\frac{z - z_0}{H}\right]$$

$$q_z = I_\infty \sigma_i n_0 \exp\left[-\frac{z - z_0}{H} - \tau_z\right]$$



Chapman weighting functions Ch(z) for $\mu = 1$ and 0.5.

Where is the peak of a Chapman function?

$$q_z = I_\infty \sigma_i n_0 \exp\left[-\frac{z - z_0}{H} - \tau_z\right]$$

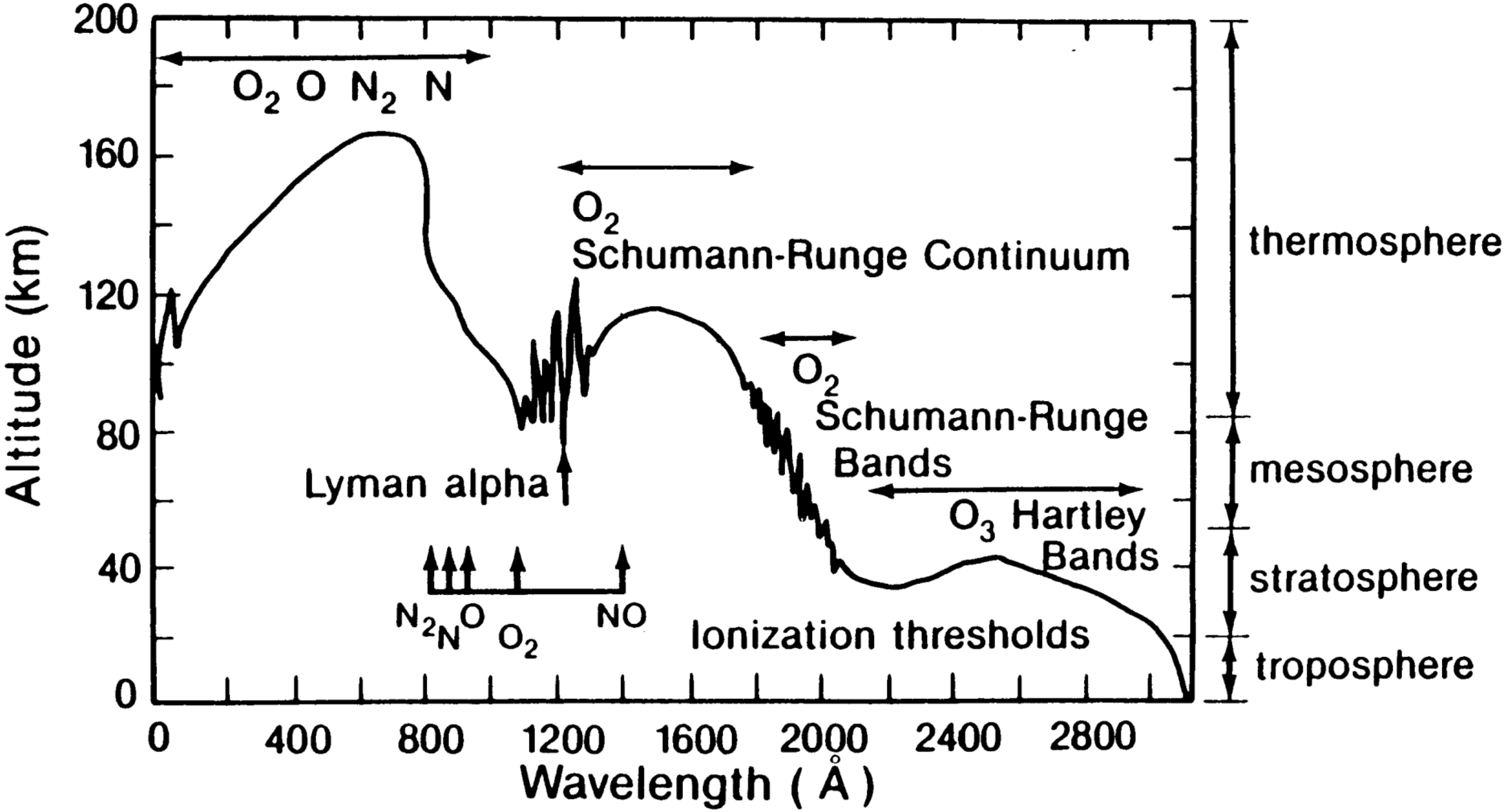
$$\tau_z = \frac{\sigma n_0 H}{\mu} \exp\left[-\frac{z - z_0}{H}\right]$$

$$\frac{dq_z}{dz} = I_\infty \sigma_i n_0 \left[-\frac{1}{H} + \frac{\tau_z}{H}\right] \exp\left[-\frac{z - z_0}{H} - \tau_z\right] = 0$$

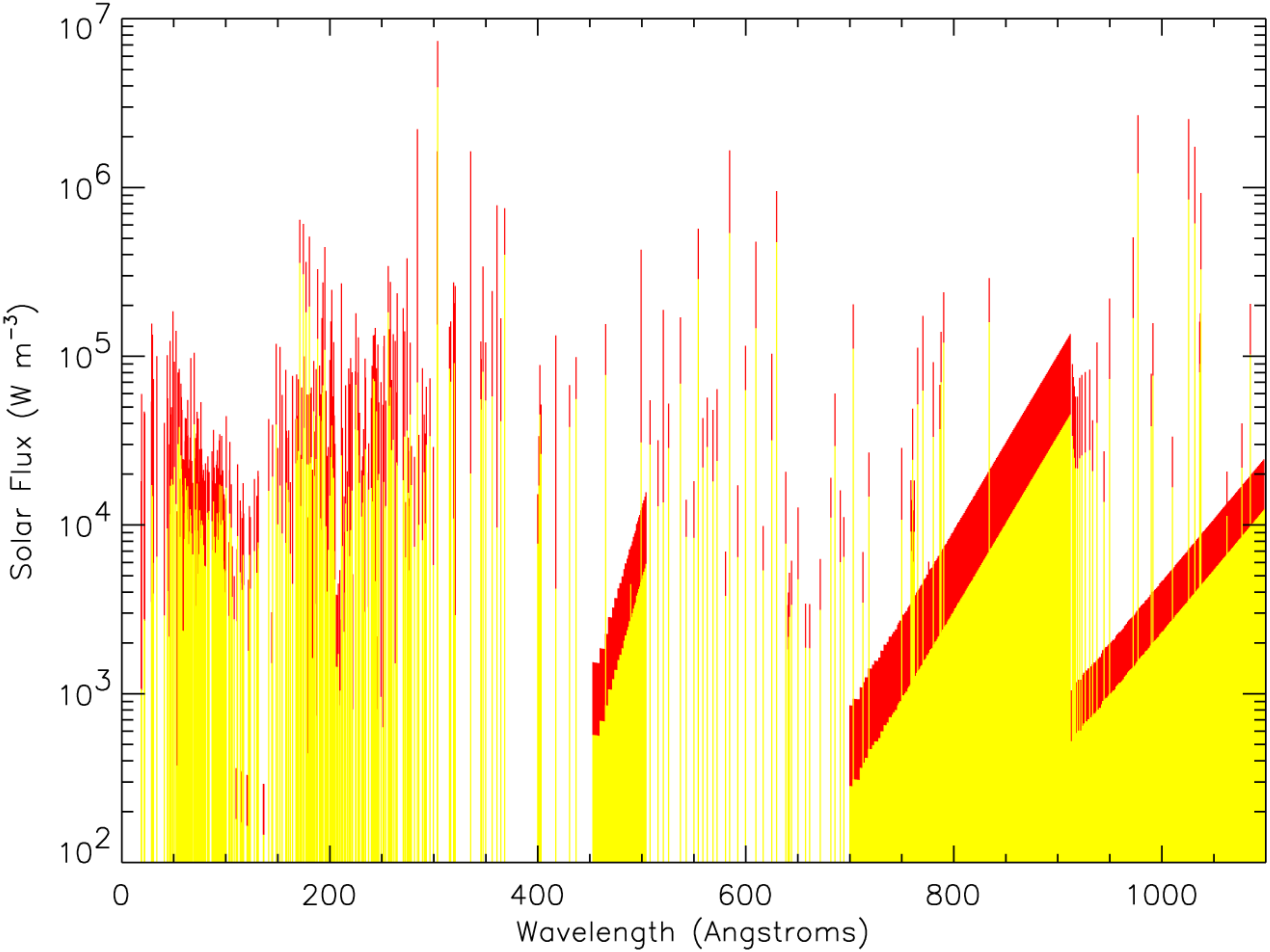
$$-\frac{1}{H} + \frac{\tau_z}{H} = 0$$

$$\tau_z = 1$$

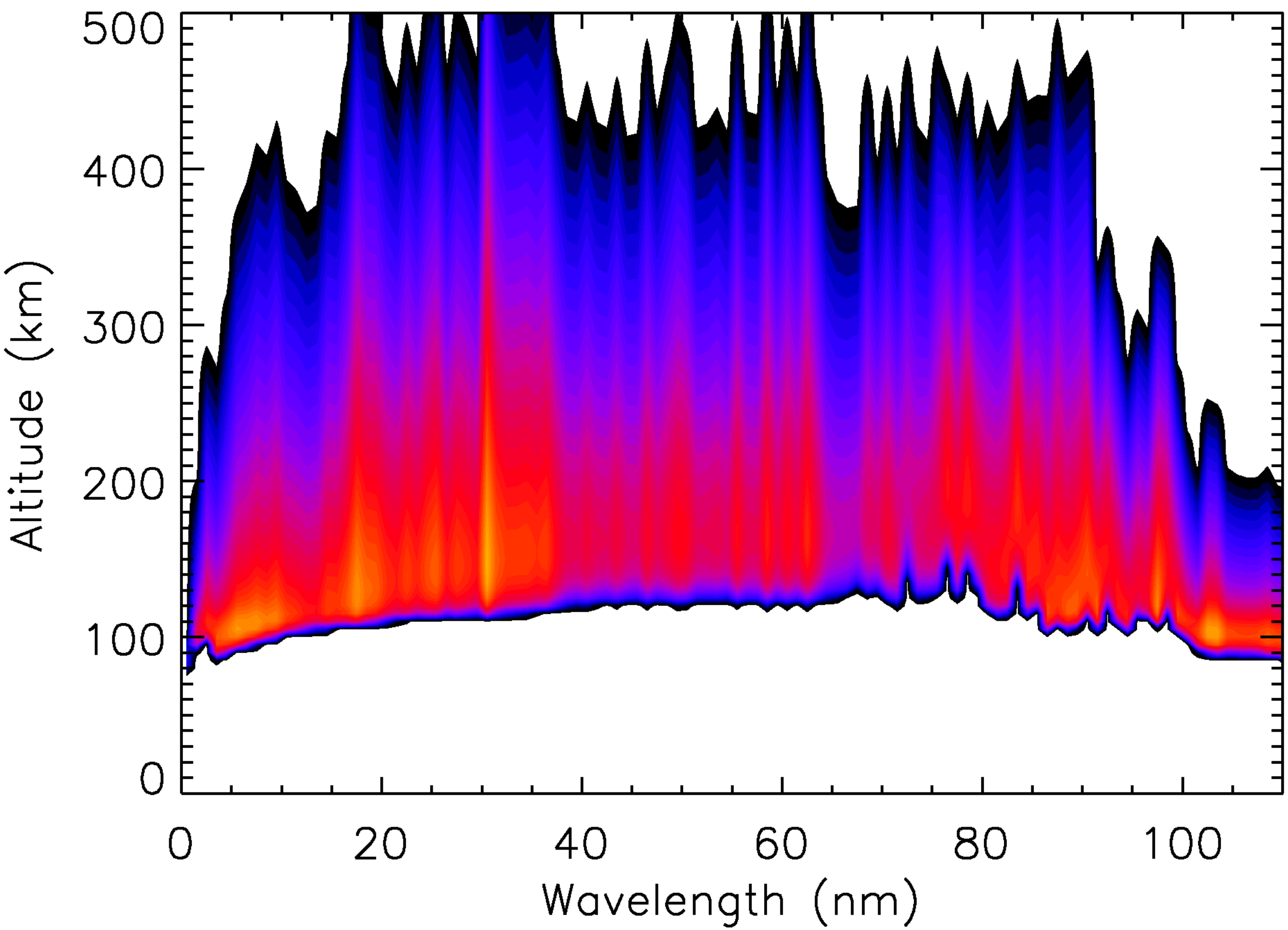
Canonical Plot of $\tau = 1$



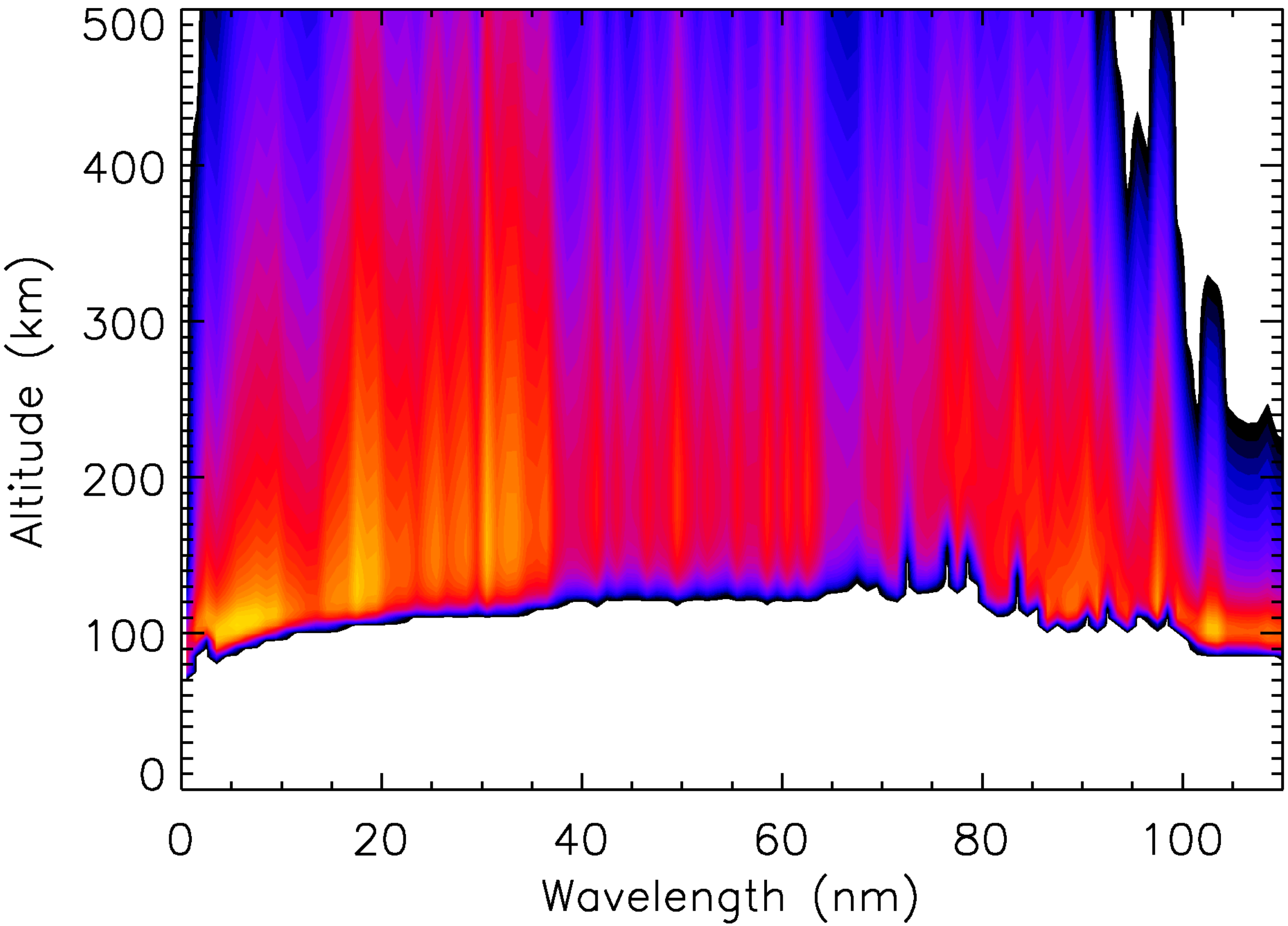
Solar Extreme-Ultraviolet and Soft X-ray Spectrum



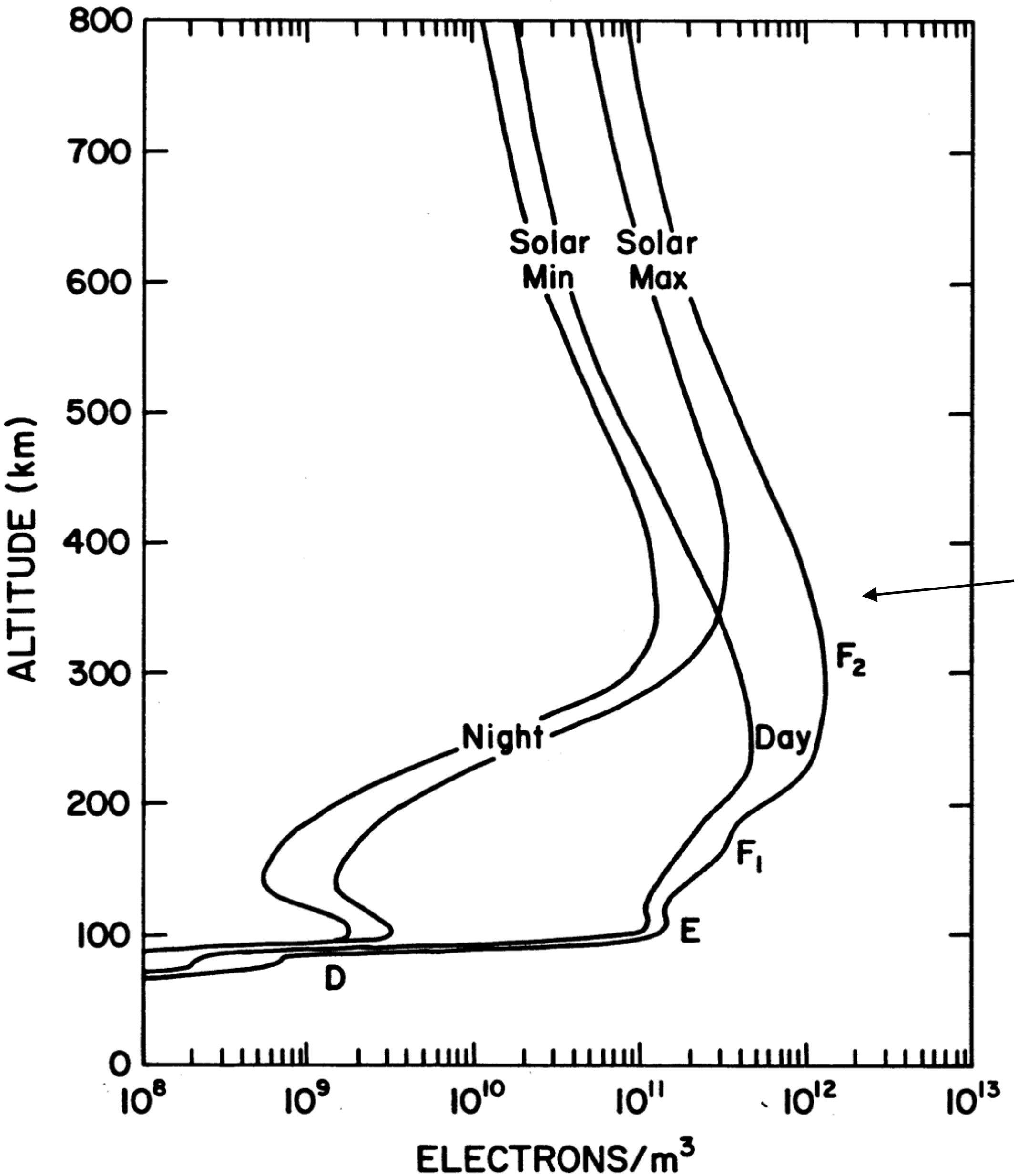
Wavelength-Dependence of Ionization Rates (solar min)



Wavelength-Dependence of Ionization Rates (solar max)

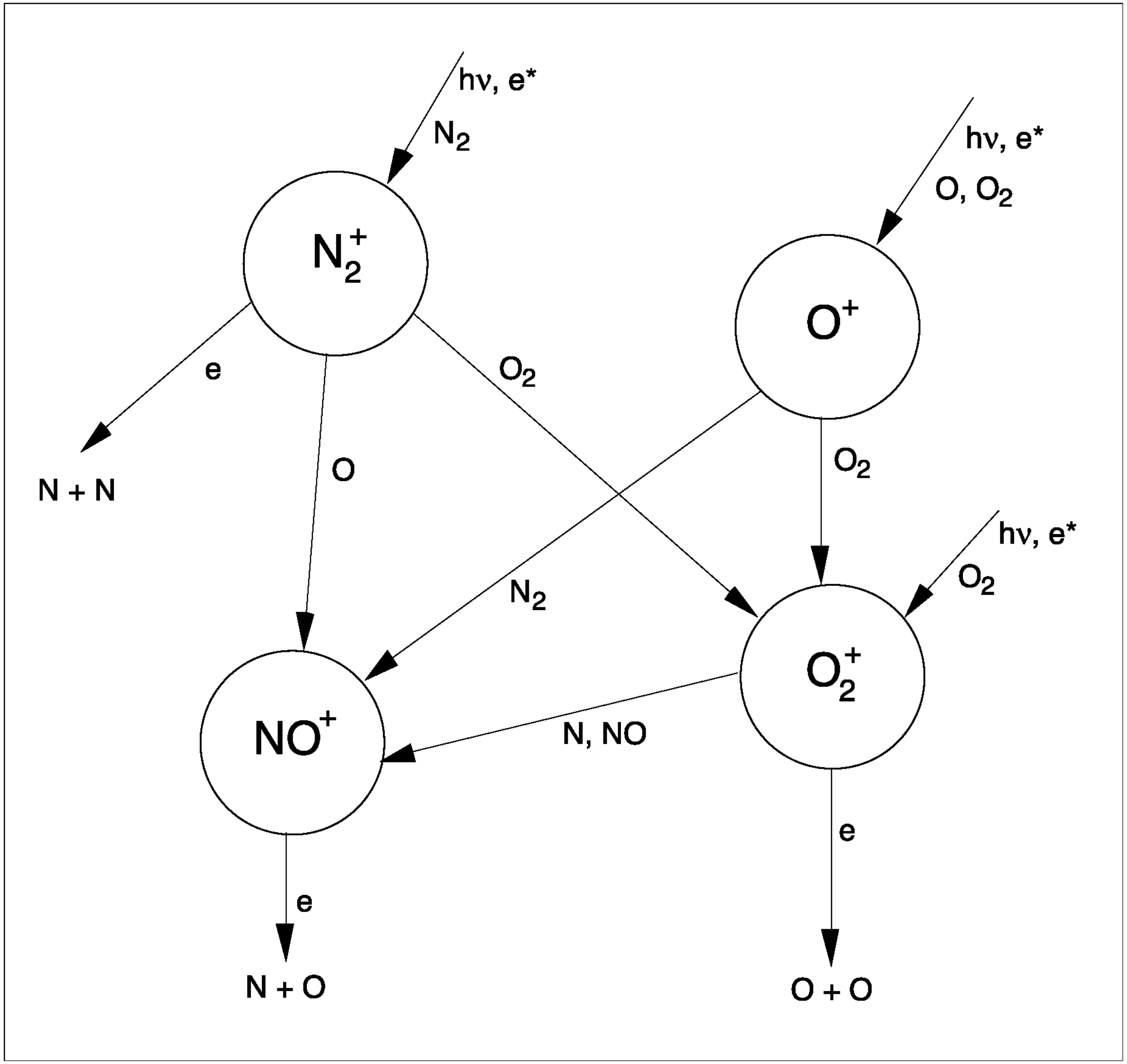


Basic Altitude Structure of the Earth's Ionosphere



What is all this ionization doing way up in here in the "*F* region" ??

Principal Ionization Processes on Earth



Types of Ionospheric Chemical Reactions

Radiative Recombination

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

slow, rate coefficients of the order of 10^{-12} cm^3 s^{-1}

Dissociative Recombination

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

fast, rate coefficients of the order of 10^{-7} cm^3 s^{-1}

Charge Exchange

$WX^+ + YZ \rightarrow WX + YZ^+$

moderately fast, rate coefficients of the order of 10^{-10} cm^3 s^{-1}

Atom-Ion Interchange

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

rate depends on the strength of the YZ bond

Simple Case – Single Species Molecular Atmosphere

$M_2 + h\nu \rightarrow M_2^+$ ionization rate q

$M_2^+ + e^- \rightarrow M + M$ rate coefficient α

Assuming photochemical equilibrium: $q = \alpha\,[M_2^+]\,[e^-]$

Assuming charge neutrality: $[e^-] = (q/\alpha)^{1/2}$

This formula approximates densities in the “E region” of Earth’s ionosphere, since it is mostly molecular ions, photochemical equilibrium applies, and most dissociative recombination rates are similar (i.e., very fast).

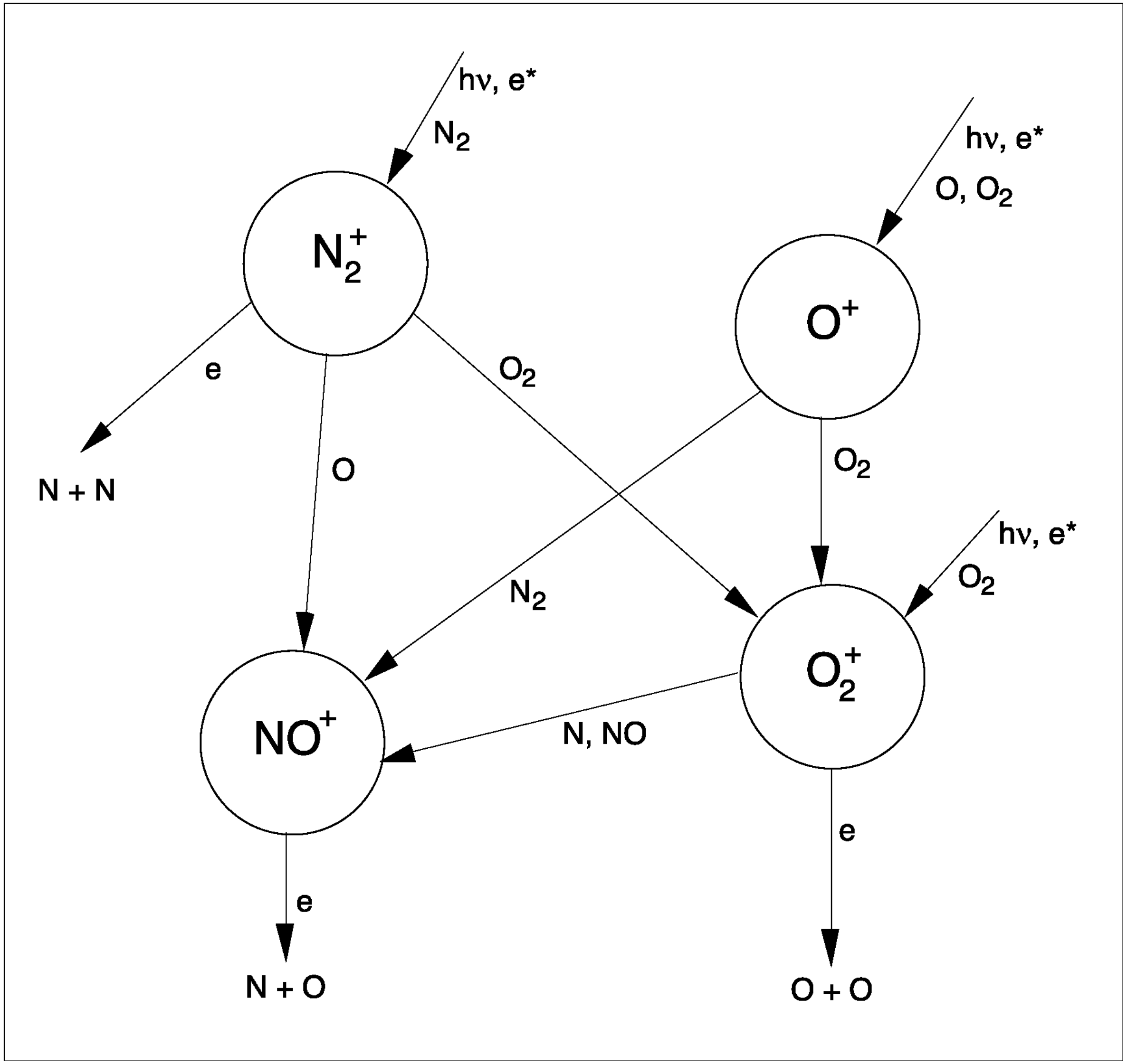
Complicated Case – Earth's *F* Region Ionosphere

Because of the decrease in molecular densities, the photochemical lifetime of O^+ becomes longer than the diffusion lifetime (the time it takes to move by a scale height in the vertical direction) above ~200 km.

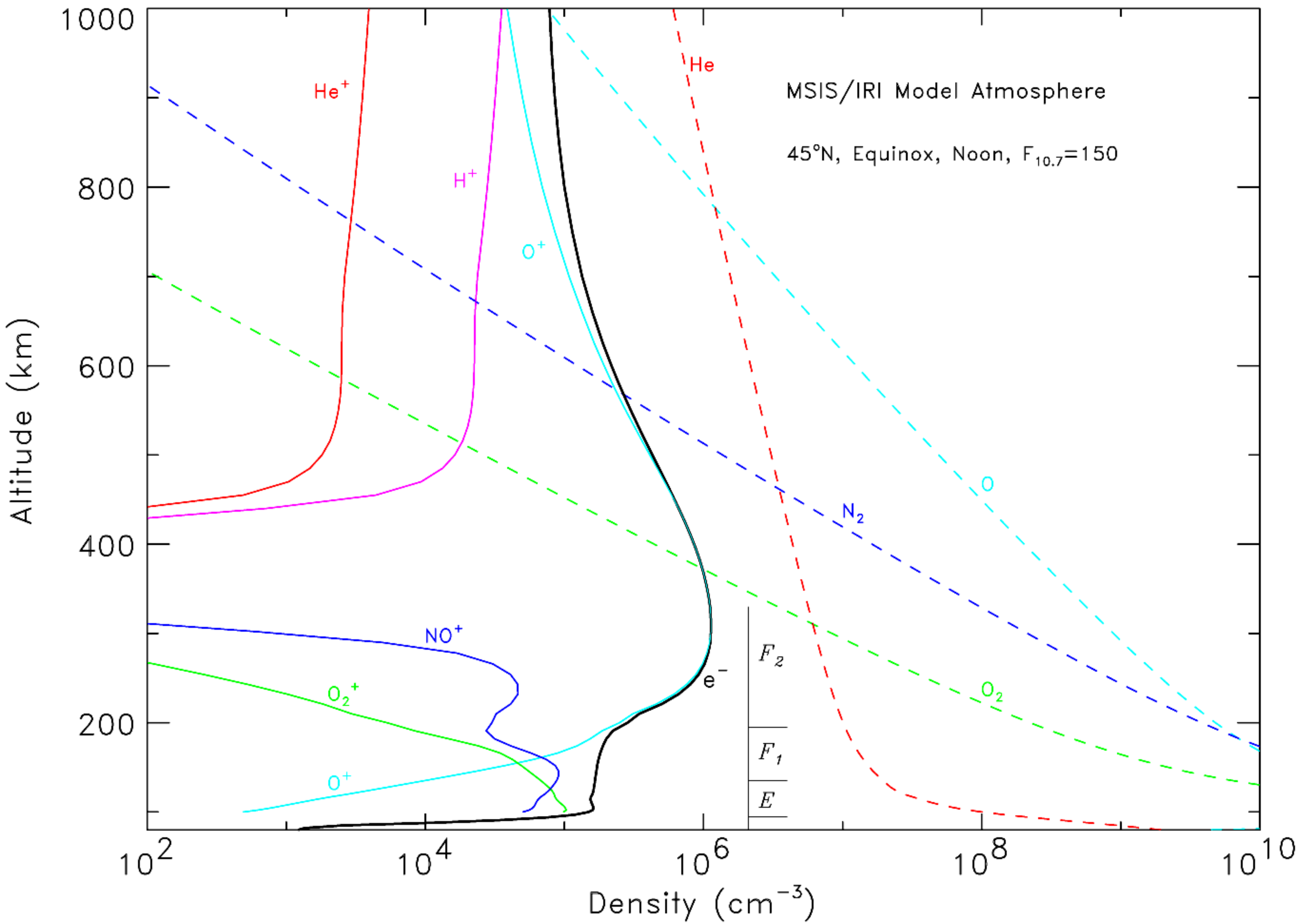
Thus, the *F* region is *not* a simple Chapman layer caused by the absorption of radiation, but rather a balance between chemical production at lower altitude and ambipolar diffusion at higher altitude.

The long lifetime of O^+ at high altitude is also why the F_2 region persists at night.

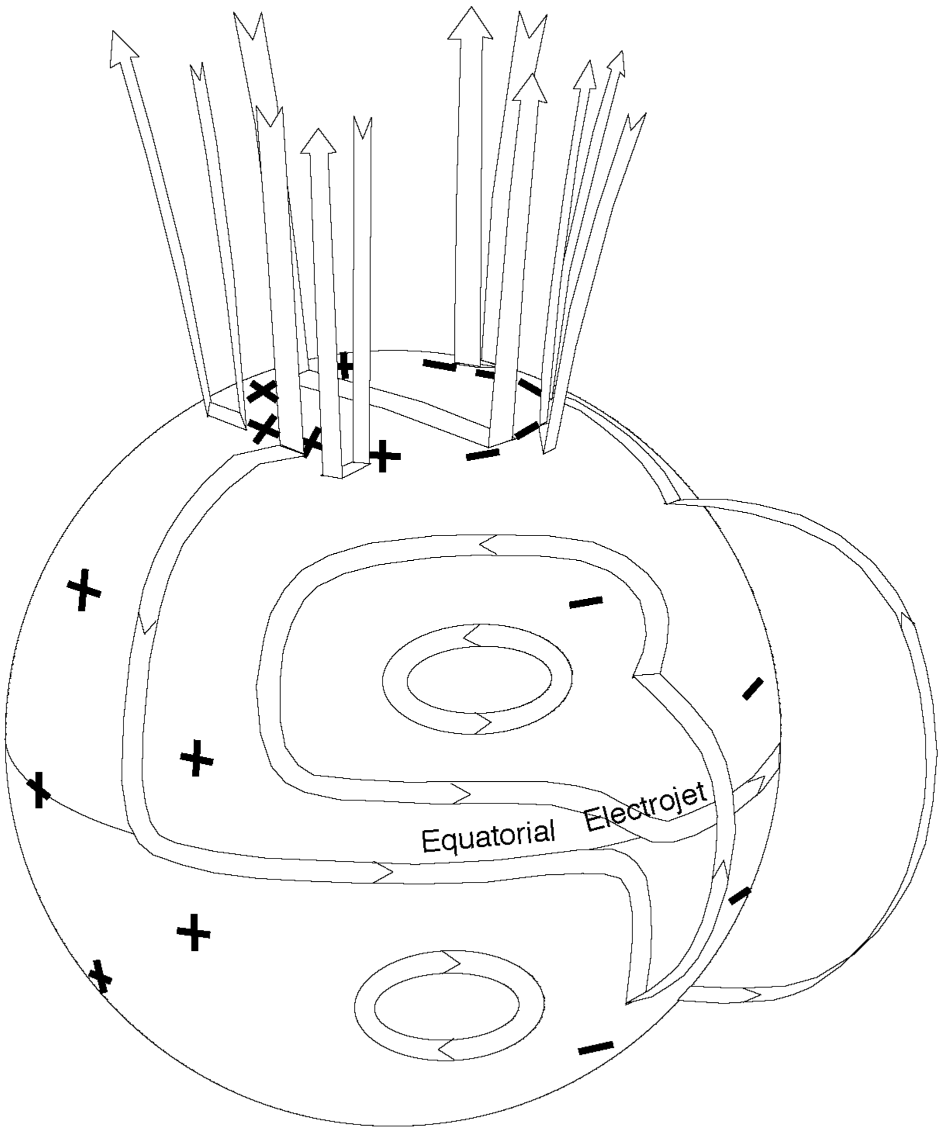
Principal Ionization Processes on Earth

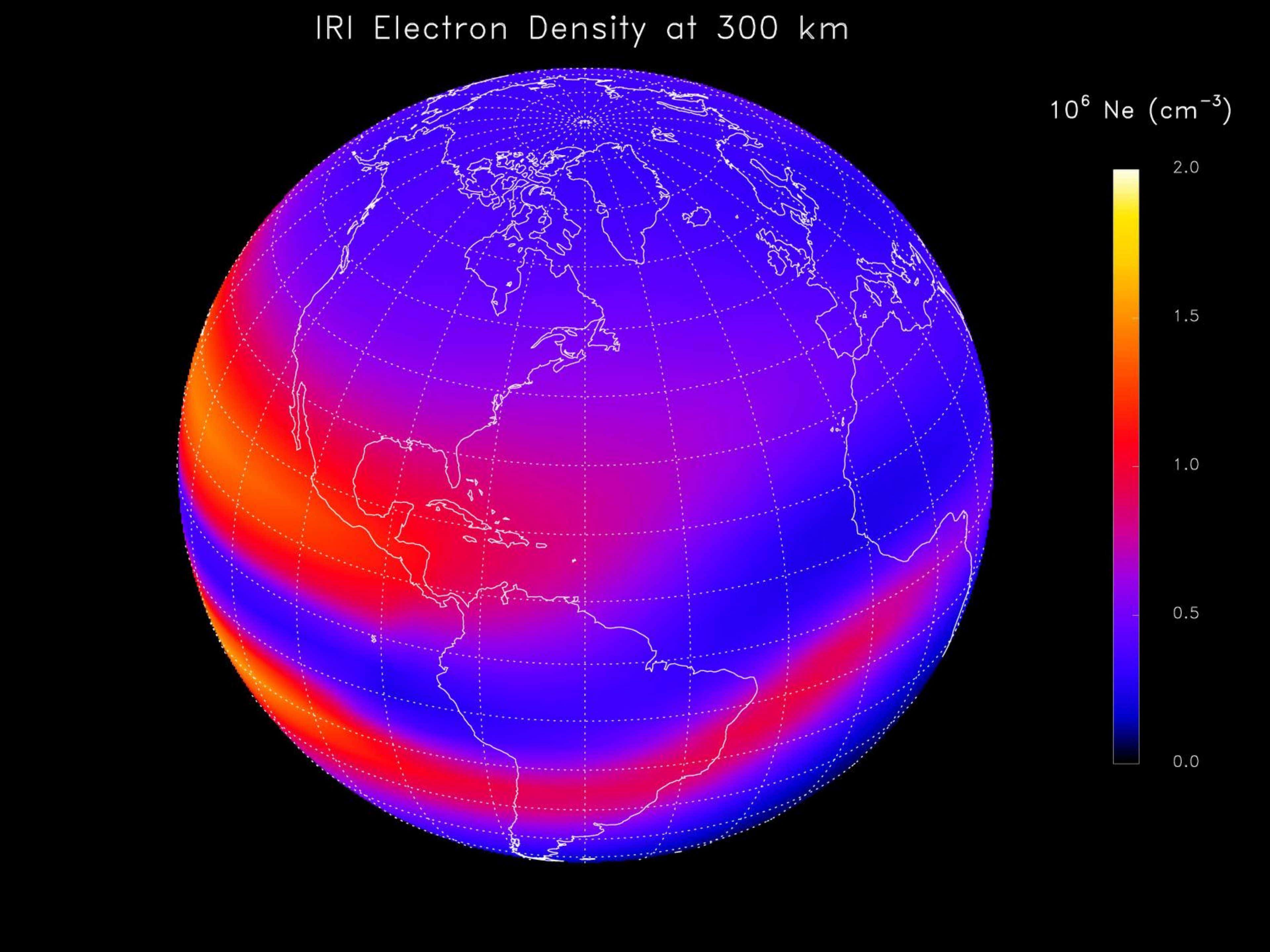


Composition of the Earth's Ionosphere

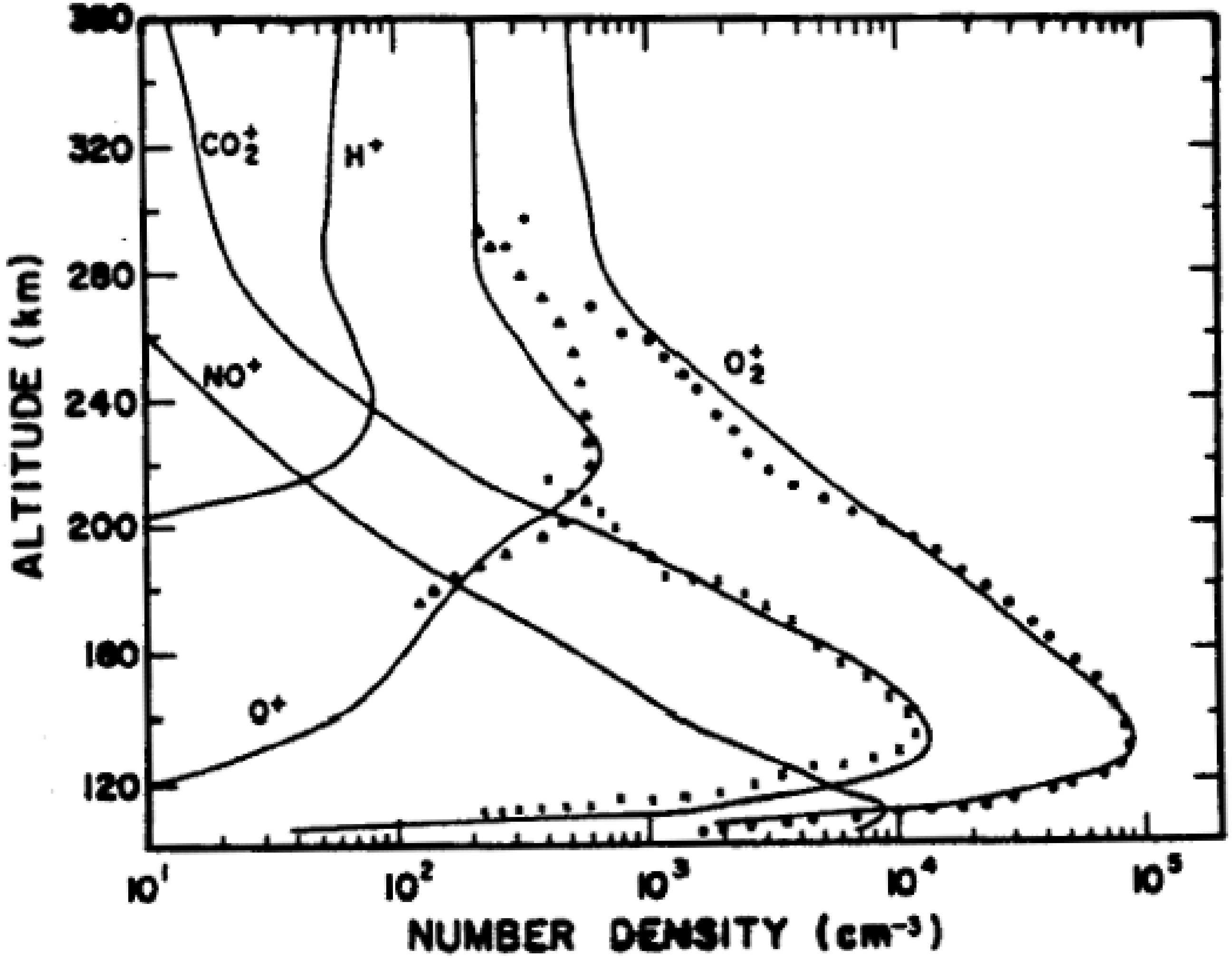


Ionospheric Electrodynamics



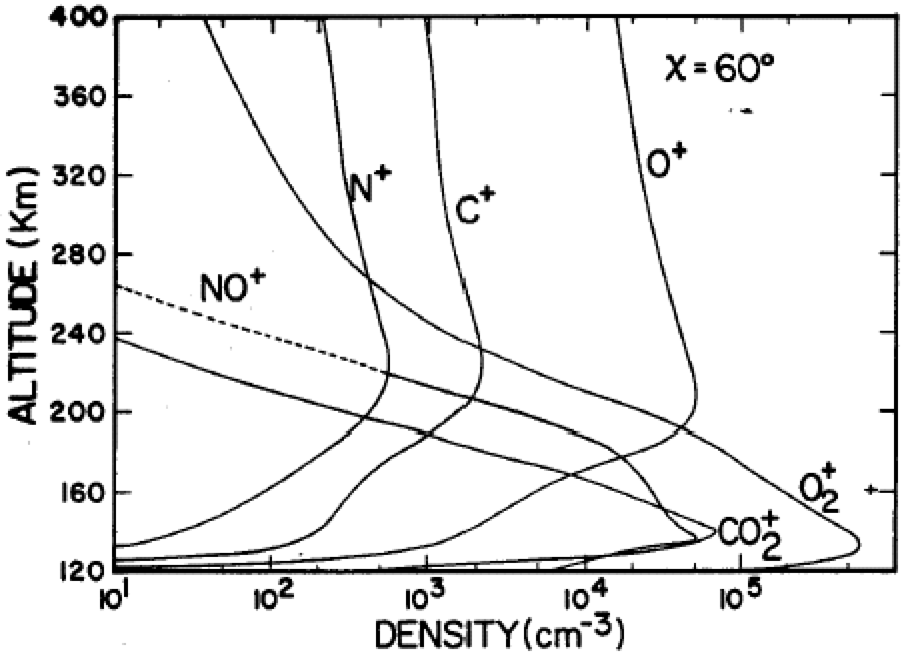

IRI Electron Density at 300 km
10⁶ Ne (cm⁻³)
2.0
1.5
1.0
0.5
0.0

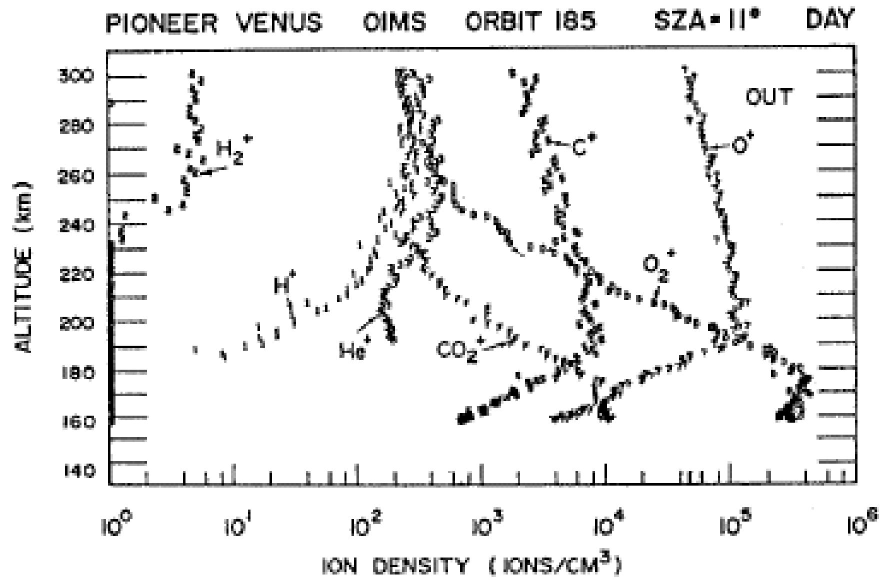
Ionospheres of Other Terrestrial Planets



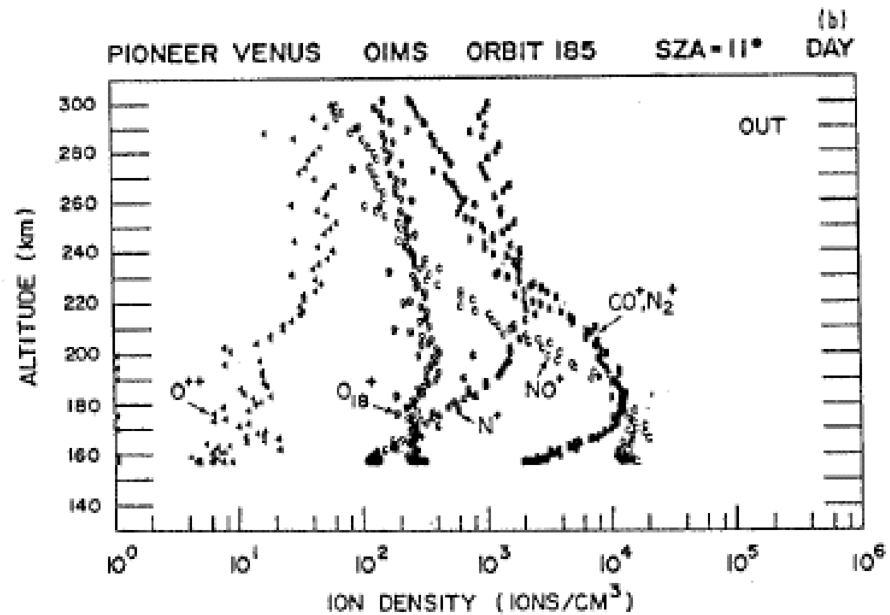
Model simulations (solid lines) and in-situ measurements from Viking-I for the dayside ionosphere of Mars.

Ionosphere of Venus





Model simulations (above) and in-situ measurements (right) made on Pioneer Venus.



Why are the ionospheres of Mars and Venus, although similar to each other, so different from Earth?

N_2^+, O_2^+ and O^+ are the most abundantly produced ions in Earth's ionosphere because N_2, O_2 and O are the most abundant neutral species in the lower part of thermosphere. However, the most abundant ions below 300 km are O^+, NO^+, and O_2^+

On Mars and Venus the most abundantly produced ions are CO_2^+ and O^+, but the most abundant ions are O_2^+ and O^+. Unlike Earth, there is no "F_2 region", and very little ionization at night.

— Why doesn't O^+ have a longer lifetime on Mars and Venus?

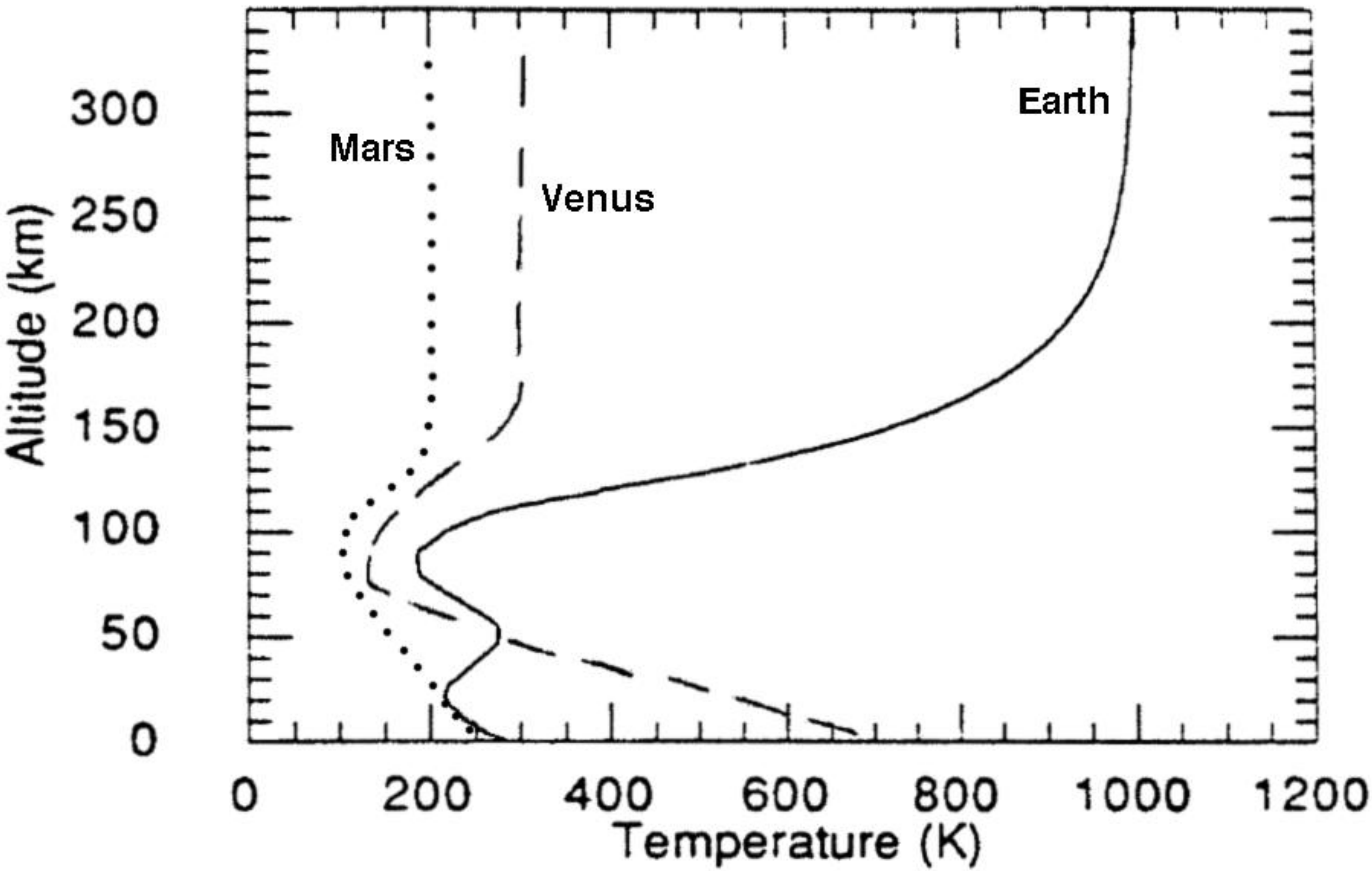
— Why is there so much O_2^+ when there's so little O_2 in their atmospheres?

Atmospheric Composition of the Terrestrial Planets

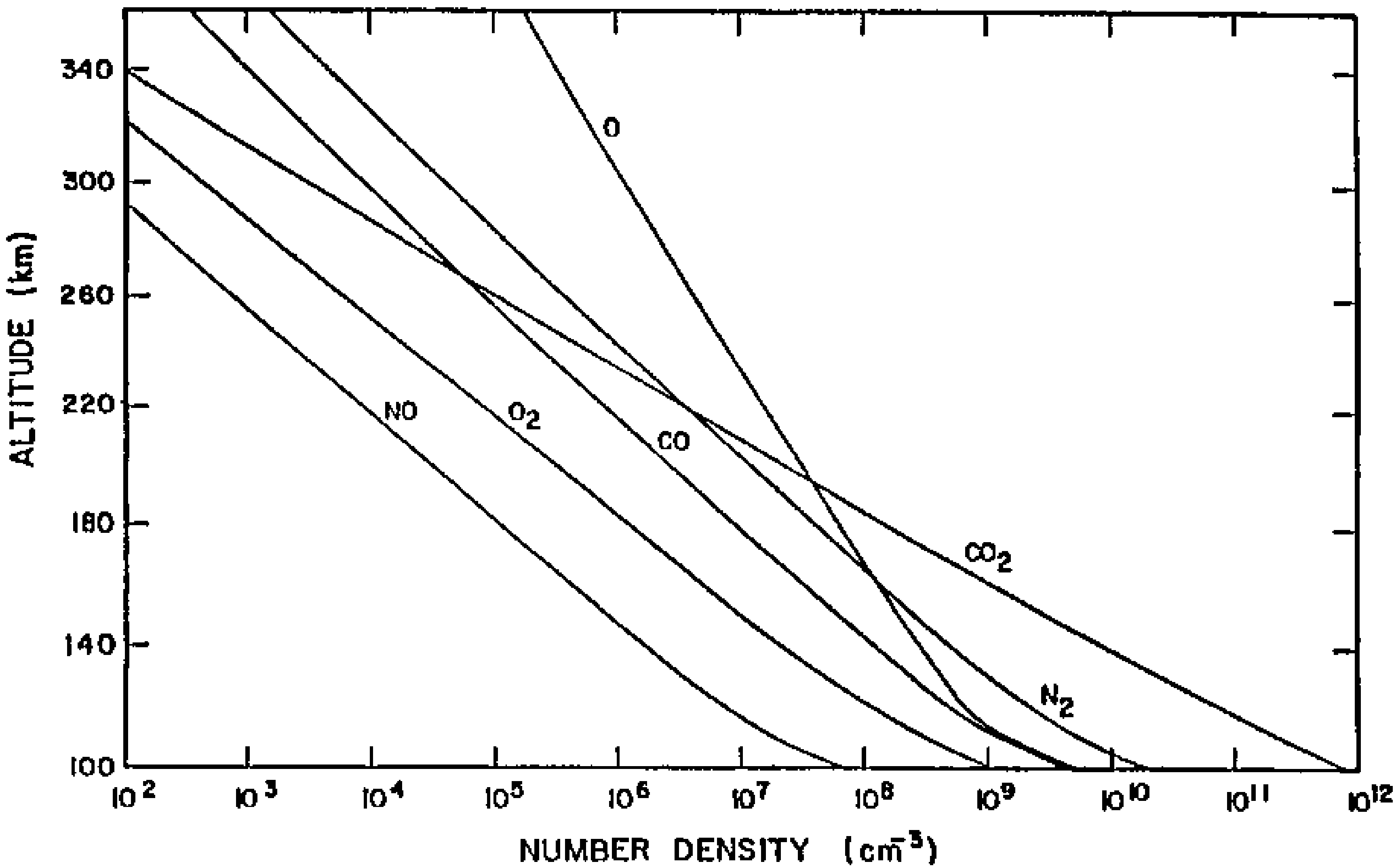
The atmospheres of Earth, Venus and Mars contain many of the same gases, but in very different absolute and relative abundances. Some values are lower limits only, reflecting the past escape of gas to space and other factors.

Planet	Molecule	Abundance (bars)	Fraction of total
Venus	CO_2	86.4	0.96
	N_2	3.2	0.035
	Ar	0.0063	0.000070
	H_2O	0.009	0.000100
Earth	N_2	0.78	0.77
	O_2	0.21	0.21
	H_2O	0.01	0.01
	Ar	0.94	0.0093
	CO_2	0.000355	0.00035
Mars	CO_2	0.0062	0.95
	N_2	0.00018	0.027
	Ar	0.00010	0.016
	H_2O	3.9×10^{-7}	0.00006

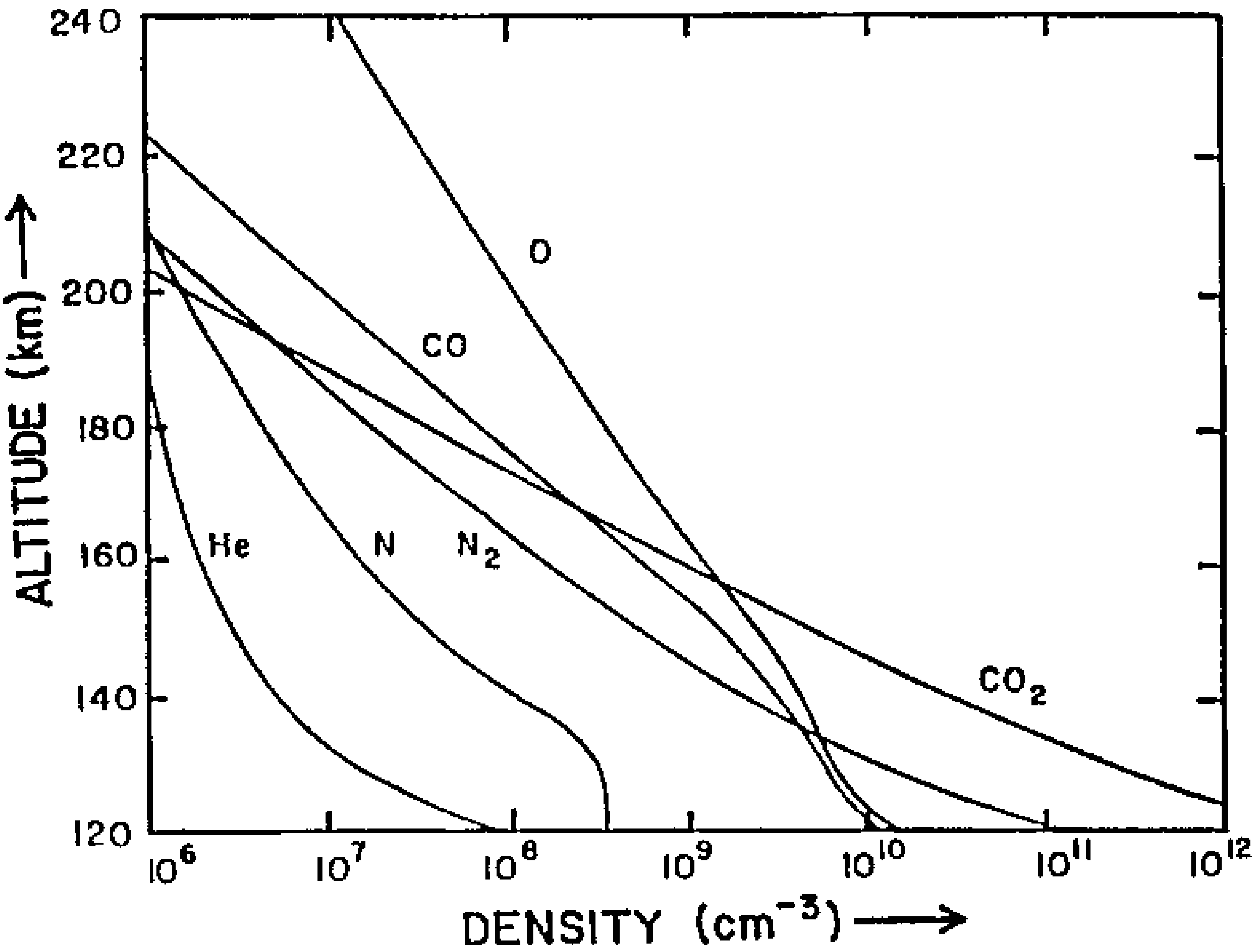
Average Temperature Profiles of the Terrestrial Planets



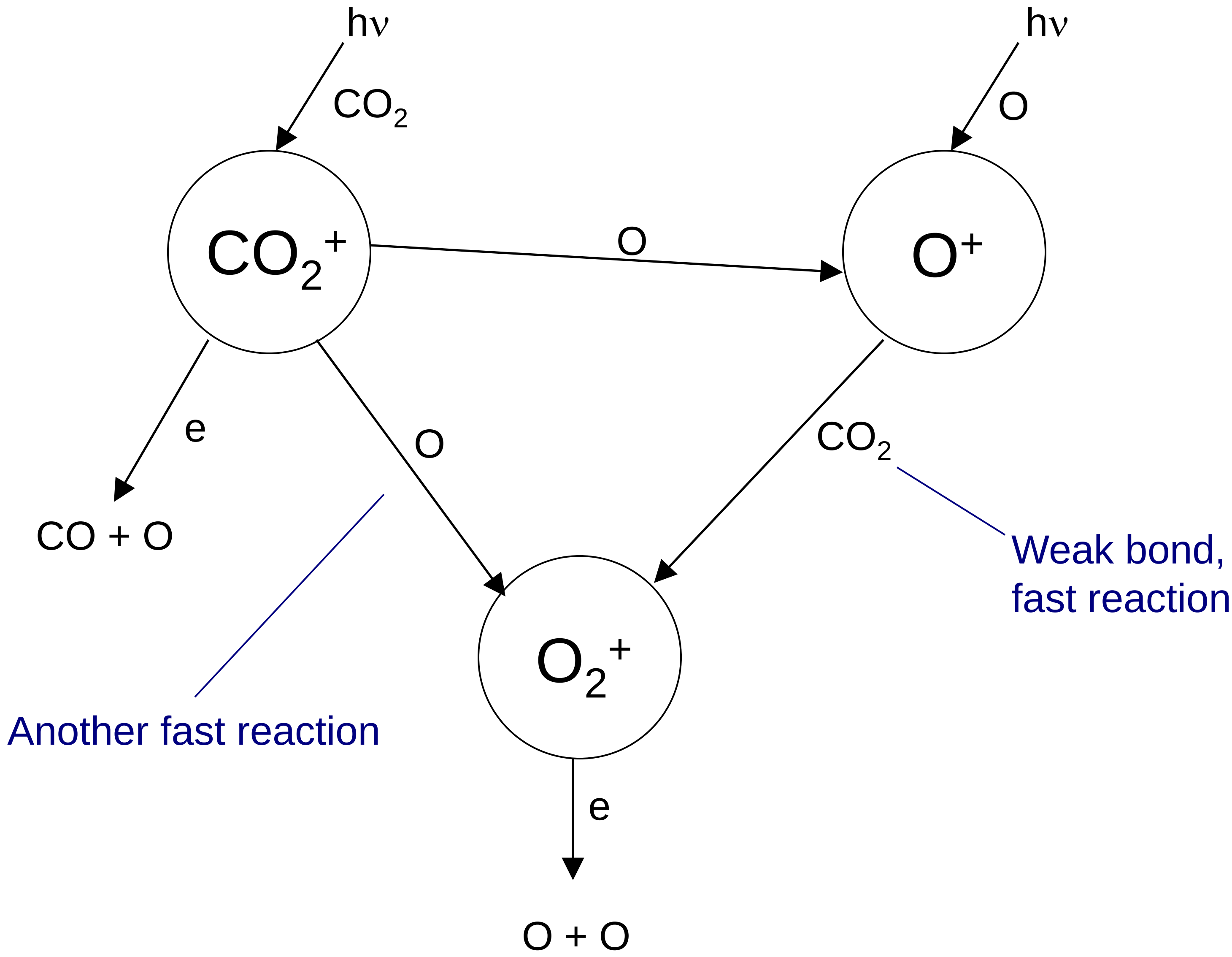
Upper Atmosphere of Mars



Upper Atmosphere of Venus



Principal Ionization Processes on Venus & Mars



Venus and Mars are "Normal", *Earth* is Anomalous

On Venus and Mars, O^+ reacts rapidly with CO_2 and CO_2^+ reacts rapidly with O because these atom-ion interchange reactions have fast rate coefficients.

This is because CO_2 is not very strongly bonded, compared to N_2.

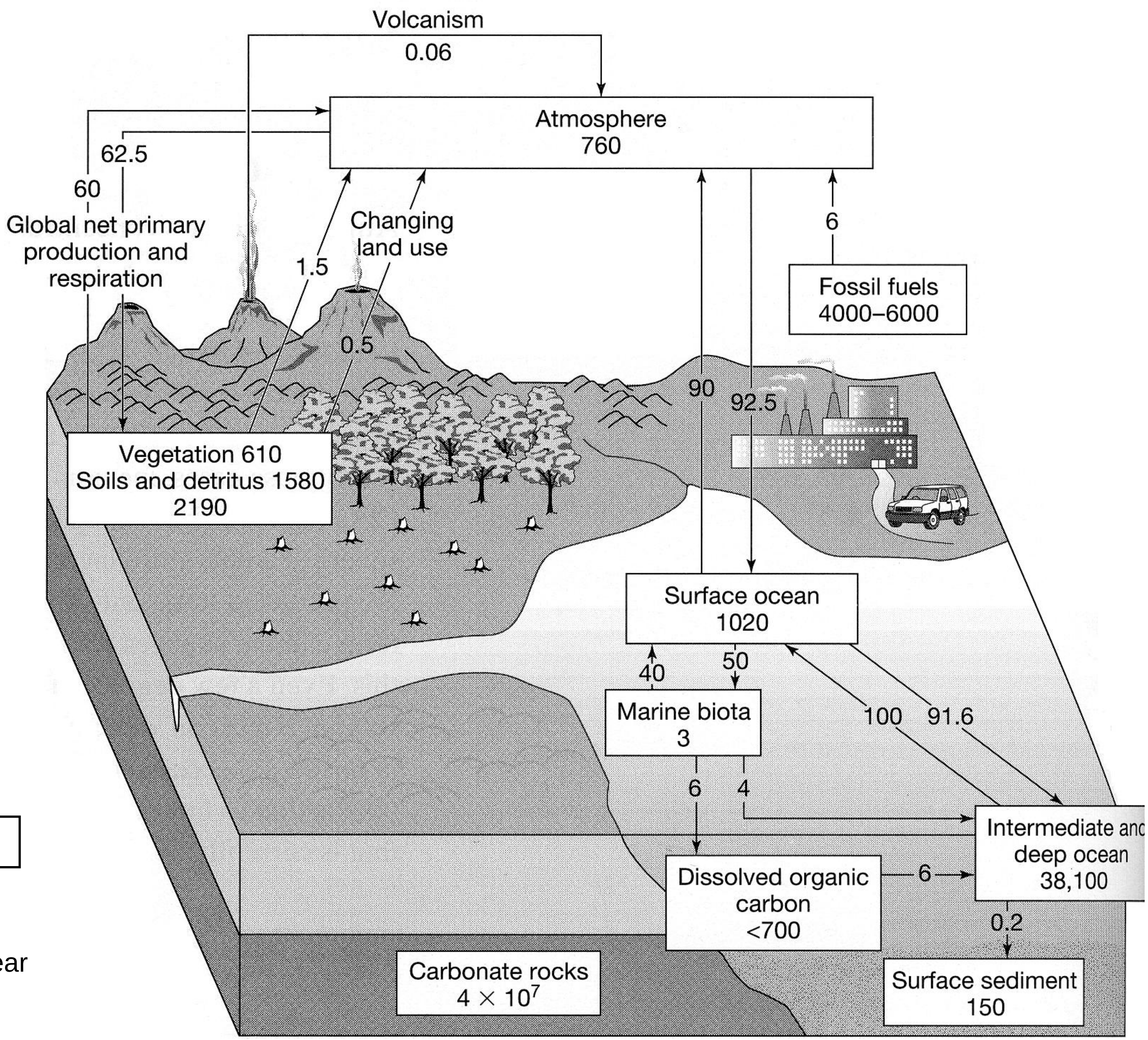
Therefore, Venus and Mars ionospheres are "*E* region" (or "F_1 region") types, controlled mostly by photochemical equilibrium at their peaks.

Earth lacks sufficient carbon in its atmosphere, and doesn't have enough O_2 at high altitude, for this to happen. Atom-ion interchange of O^+ with N_2 is very slow, due to the strength of the N_2 bond. This creates the high, dense, persistant "F_2 region" and a lot of interesting ionospheric variability.

So…

Where's the Carbon?

The Earth's Carbon Cycle



Gigatons

Gigatons/Year

Another Question for Discussion

A high, dense, "F_2 layer" ionosphere observed on a terrestrial-type planet would be a sign of life on that planet.

1. True
2. False