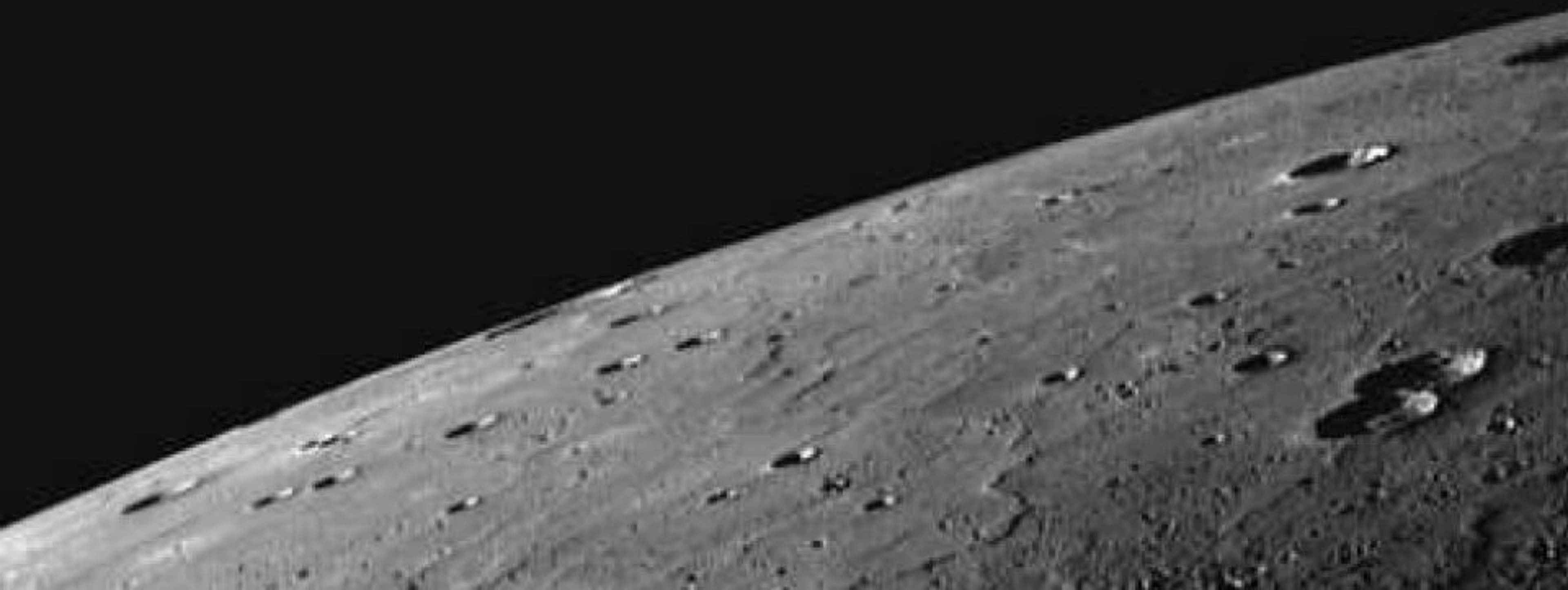
Sunset from the International Space Station. Credit: Expedition 23 Crew, NASA

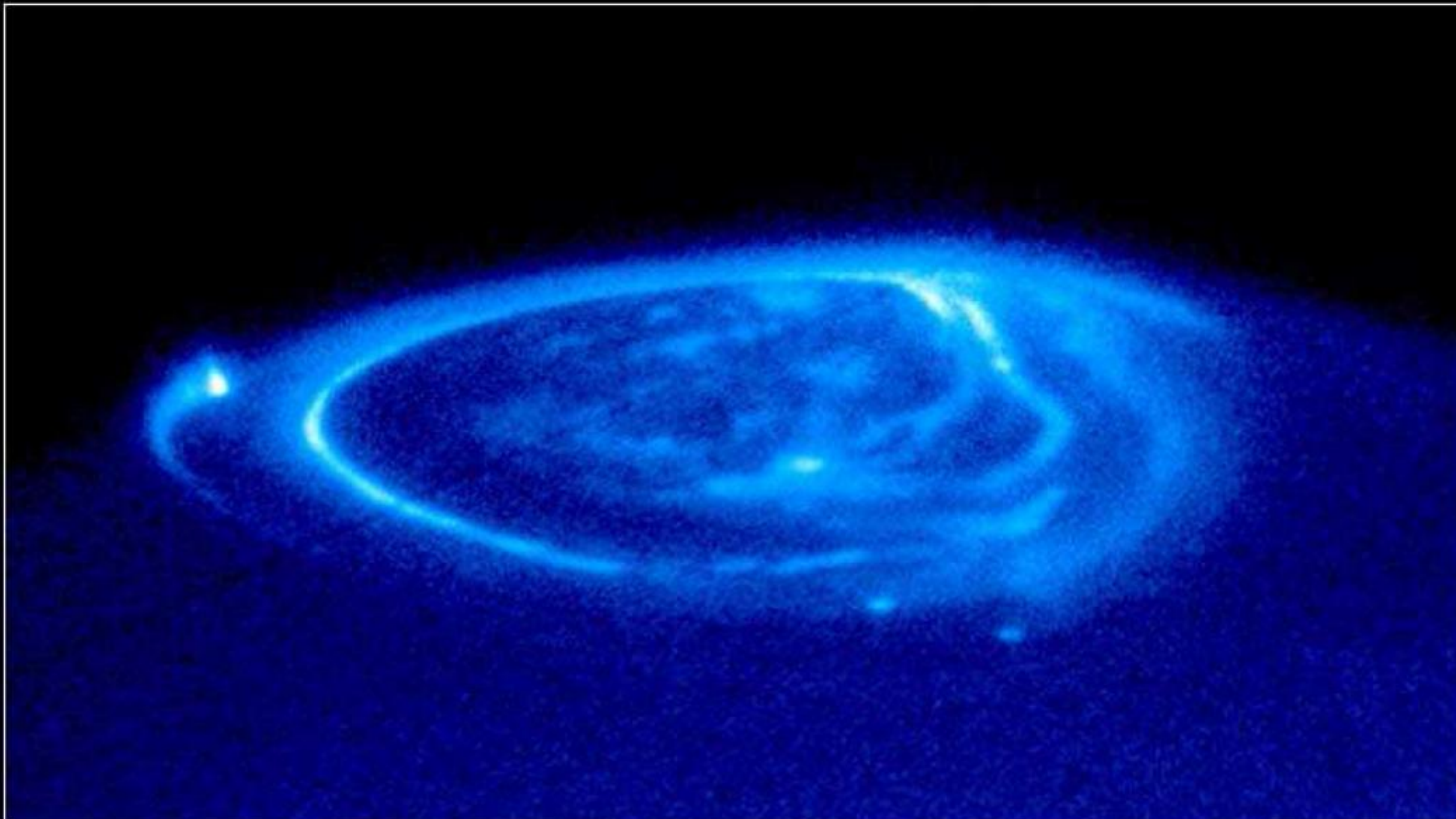
Titan’s upper atmosphere seen by Cassini. Credit: NASA

High-resolution Look over Mercury's Northern Horizon. The surface-bound exosphere be seen in this image. Credit: MESSENGER team



Aurora Borealis (Northern Lights) over Alaska. Credit: US Air Force, J. Strang

Aurora Australis (Southern Lights) seen from the International Space Station. Credit: NASA

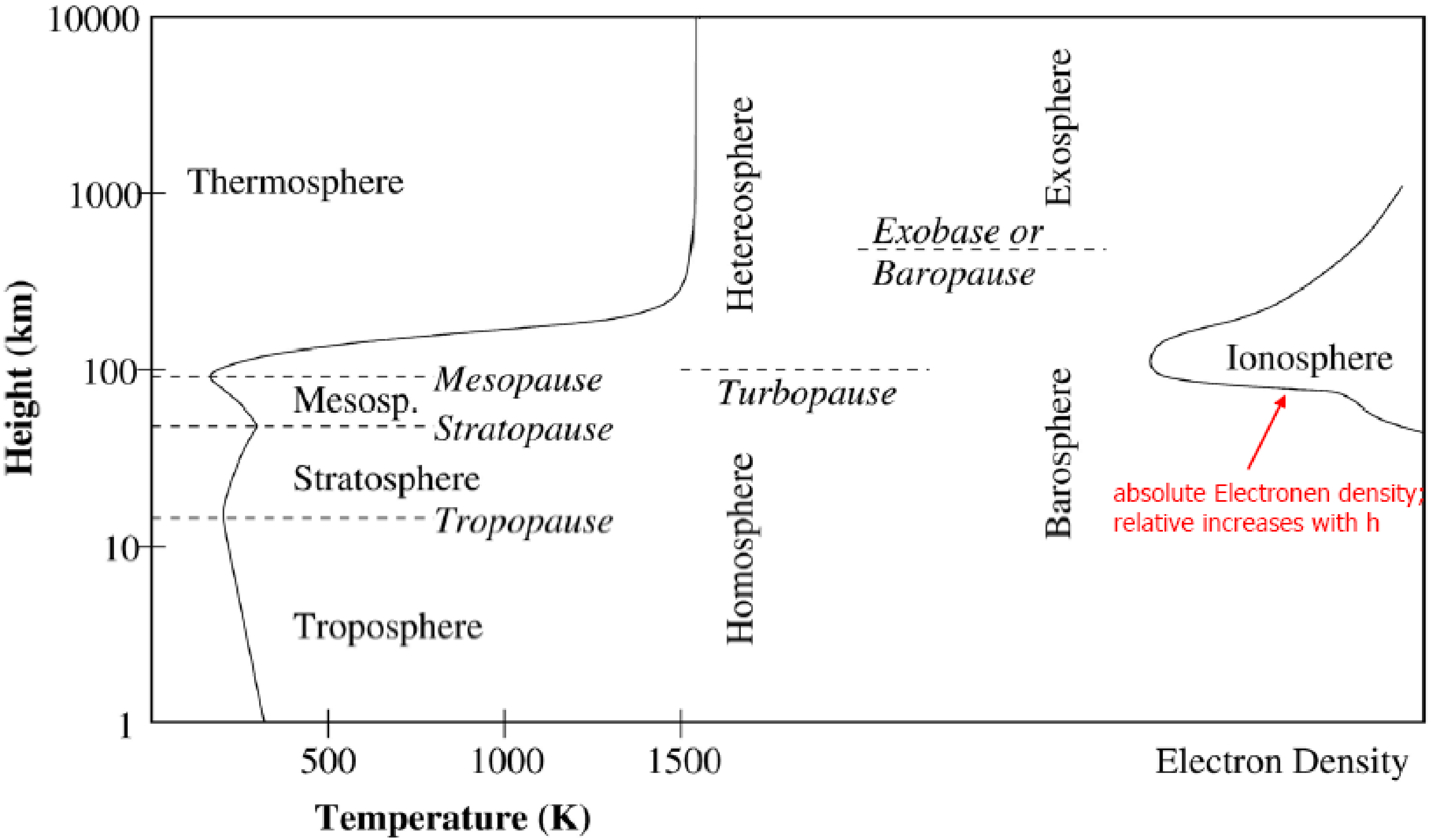


Jupiter Aurora HST • STIS

NASA and J. Clarke (University of Michigan) • STScI-PRC00-38

UV image of auroras around the Jupiter pole. Bright streaks due to magnetic-flux tubes to Io, Ganymede, and Europa. Credit: John T. Clarke (U. Michigan), ESA, NASA

Atmospheric Layers



Horizontal Structure of the Terrestrial Atmosphere

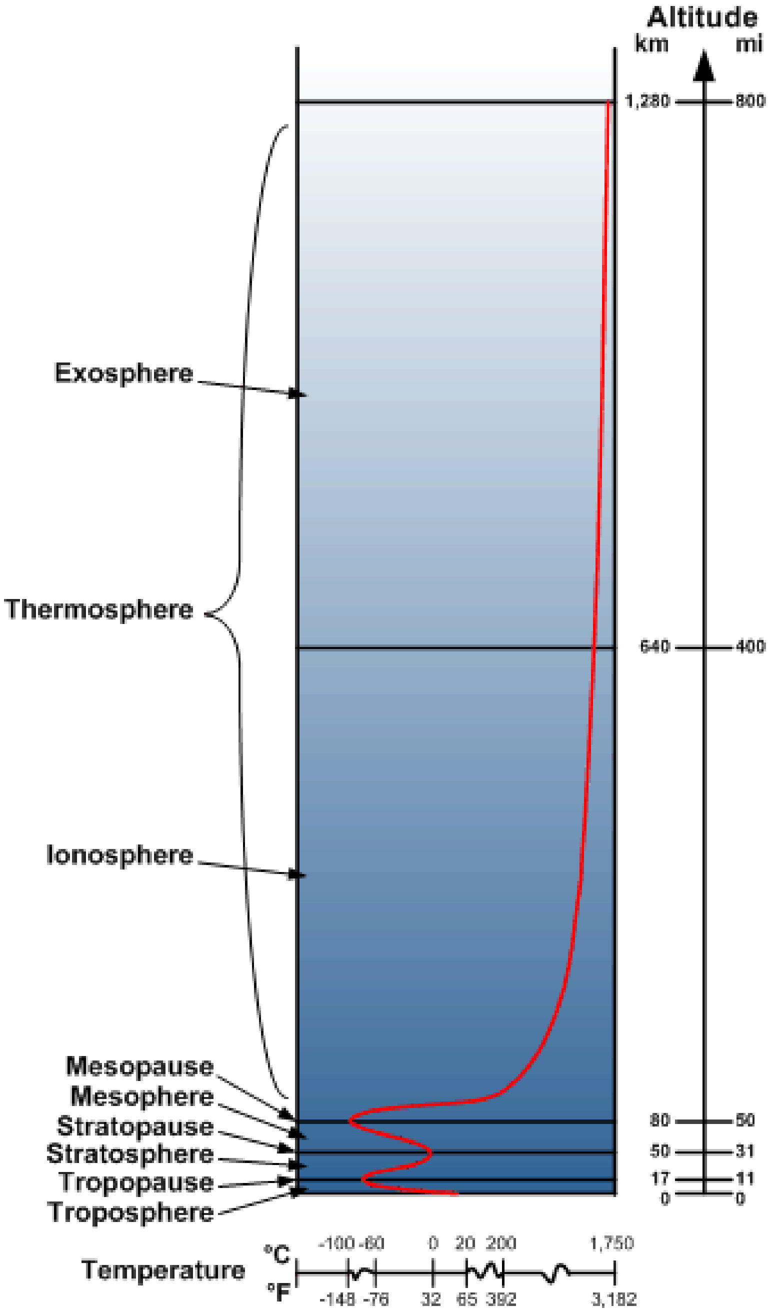
Atmos. Layers

Classified by Gravitational binding

- Barosphere
  - 0 km→ 600 km
  - binding
- Exosphere
  - > 600 km
  - Escaping or evaporation

Classified by Composition

- Homosphere
  - 0 km→ 100 km
  - Homogeneous
- Heterosphere
  - 100 km → ~2000 km
  - Inhomogeneous
- Hydrogensphere (Geocorona)
  - > ~2000 km
  - Dominated by hydrogen



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):

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

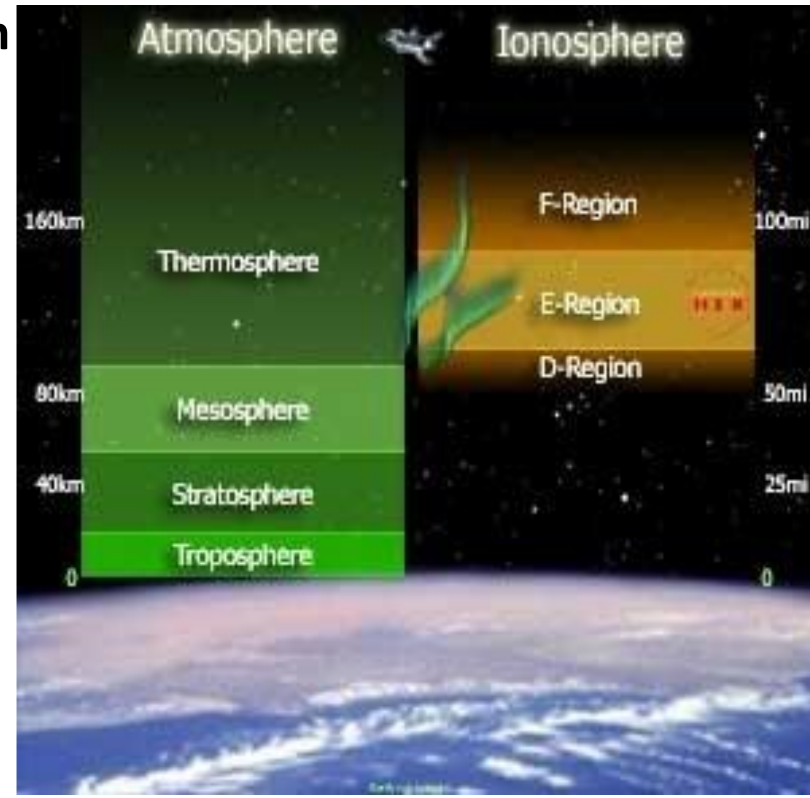
m_i is the molecular weight of individual species

— *Each species follows its own scale height.*

The Ionosphere

What is the Ionosphere?

- **The atmosphere above ~70km that is partially ionized by ultraviolet radiation from the sun (charged atmosphere)**
  - **This region of partially ionized gas extends upwards to high altitudes where it merges with the magnetosphere**
- **Discovered in the early 1900s in connection with long distance radio transmissions**
  - **Scientists postulated, and later proved, that long distance radio communication was possible due to reflection off of an ionized region in the atmosphere**



1874: born in Italy

1895: 1.5 mile wireless

1899: cross English Channel

1901: cross Atlantic ocean

1909: Nobel Prize in Physics

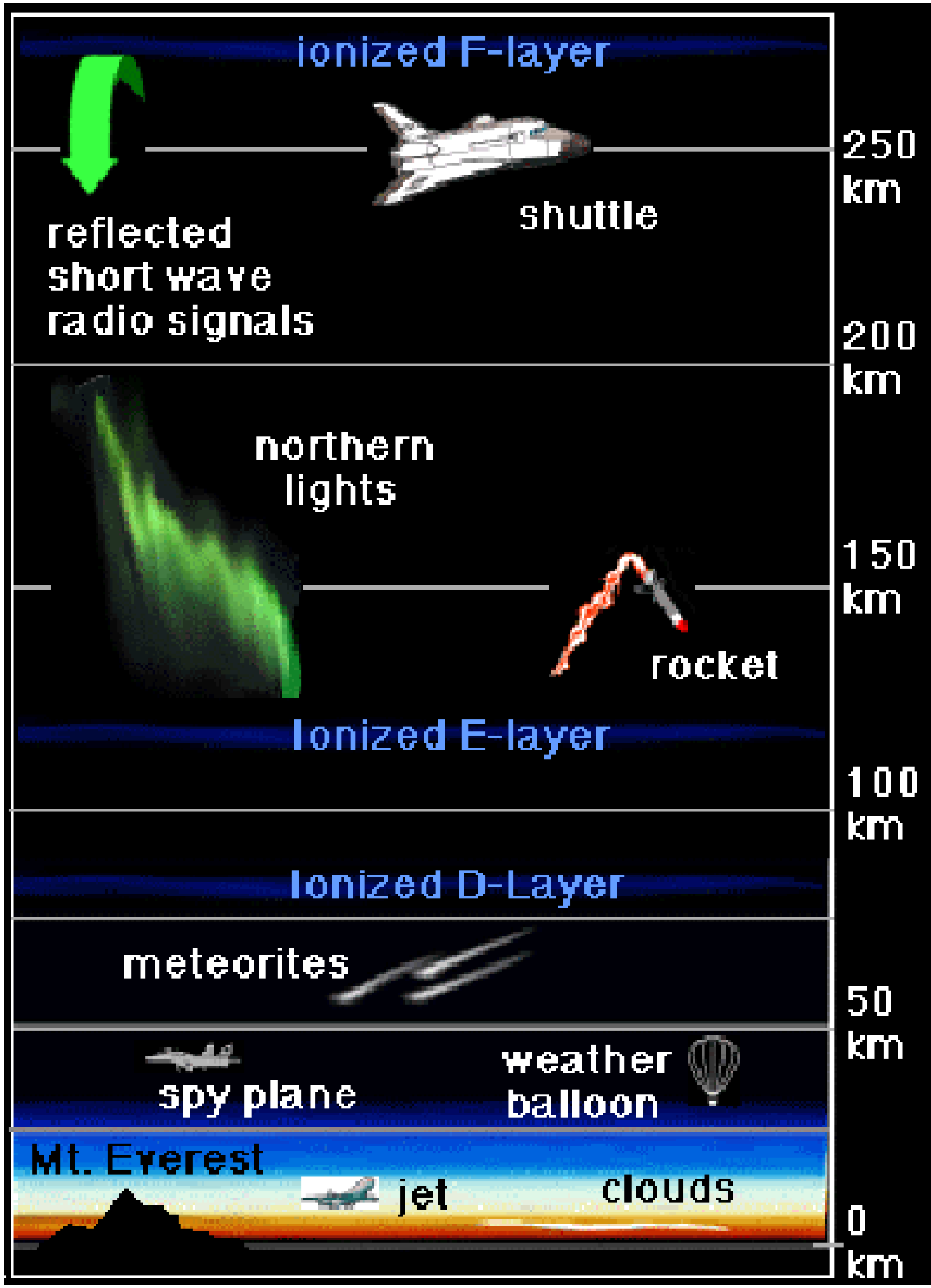
Existence of ionosphere suggested -- by Gauss, Lord Kelvin and Stewart Balfour in the 19th century

First direct verification of its existence -- - Marconi in 1901 succeeded in sending radio signals across the Atlantic

- Arthur Kennelly and Oliver Heaviside independently in 1902 postulated an ionized atmosphere to account for radio transmissions. (Kennelly-Heavyside layer is now called the E-layer).

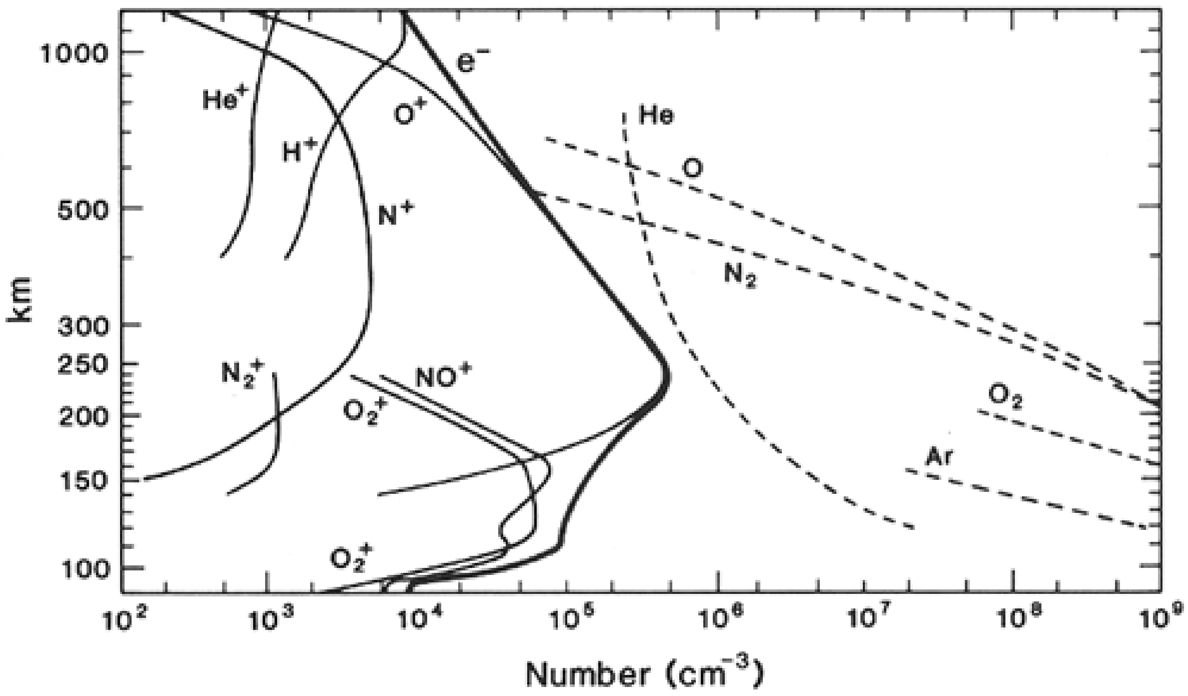
'ionosphere' coined by R.A. Watson in 1926

First direct evidence of an ionosphere on a planet other than earth -- radio occultation measurements by Mariner 5 as it flew by Venus on October 19, 1967



The Ionosphere is a Weakly Ionized Plasma

Neutral density exceeds the electron or ion density below about 500 km

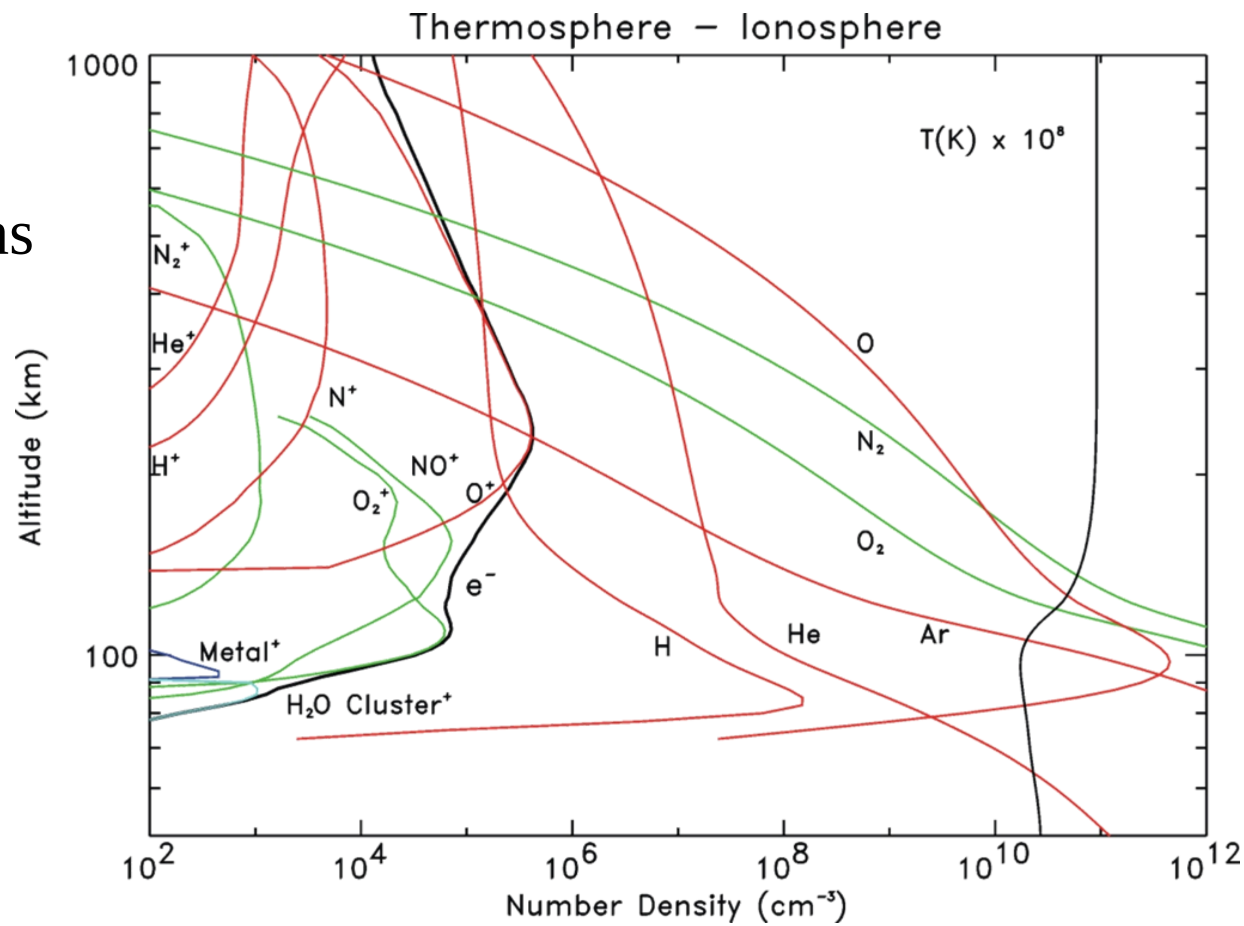


broad definition: ***"the ionosphere is that region of the atmosphere (or gaseous envelope) surrounding a solar system body where significant numbers of low-energy free electrons and ions are present"***

Ionosphere Structure

Ionosphere:
- Weak ionization
- Electrons and ions represent trace gases

- Ion/neutral ratio (n/n_n)
- 10^{-8} at 100 km
- 10^{-3} at 300 km
- 10^{-2} at 1000 km



How is the Ionosphere Created?

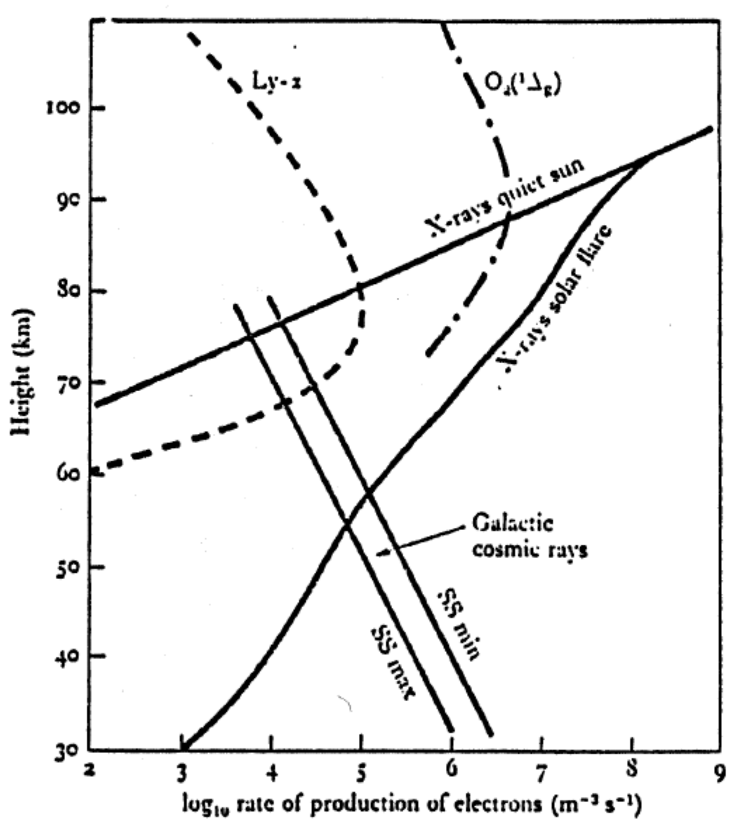
- For practical purposes the ionosphere can be thought of as quasi-neutral (the net charge is practically zero in each volume element with enough particles).
- The ionosphere is formed by ionization of the three main atmospheric constituents N_2, O_2, and O.
  - The primary ionization mechanism is photoionization by extreme ultraviolet (EUV) and X-ray radiation.
  - In some areas ionization by particle precipitation is also important.
  - The ionization process is followed by a series of chemical reactions which produce other ions.
  - Recombination removes free charges and transforms the ions to neutral particles.

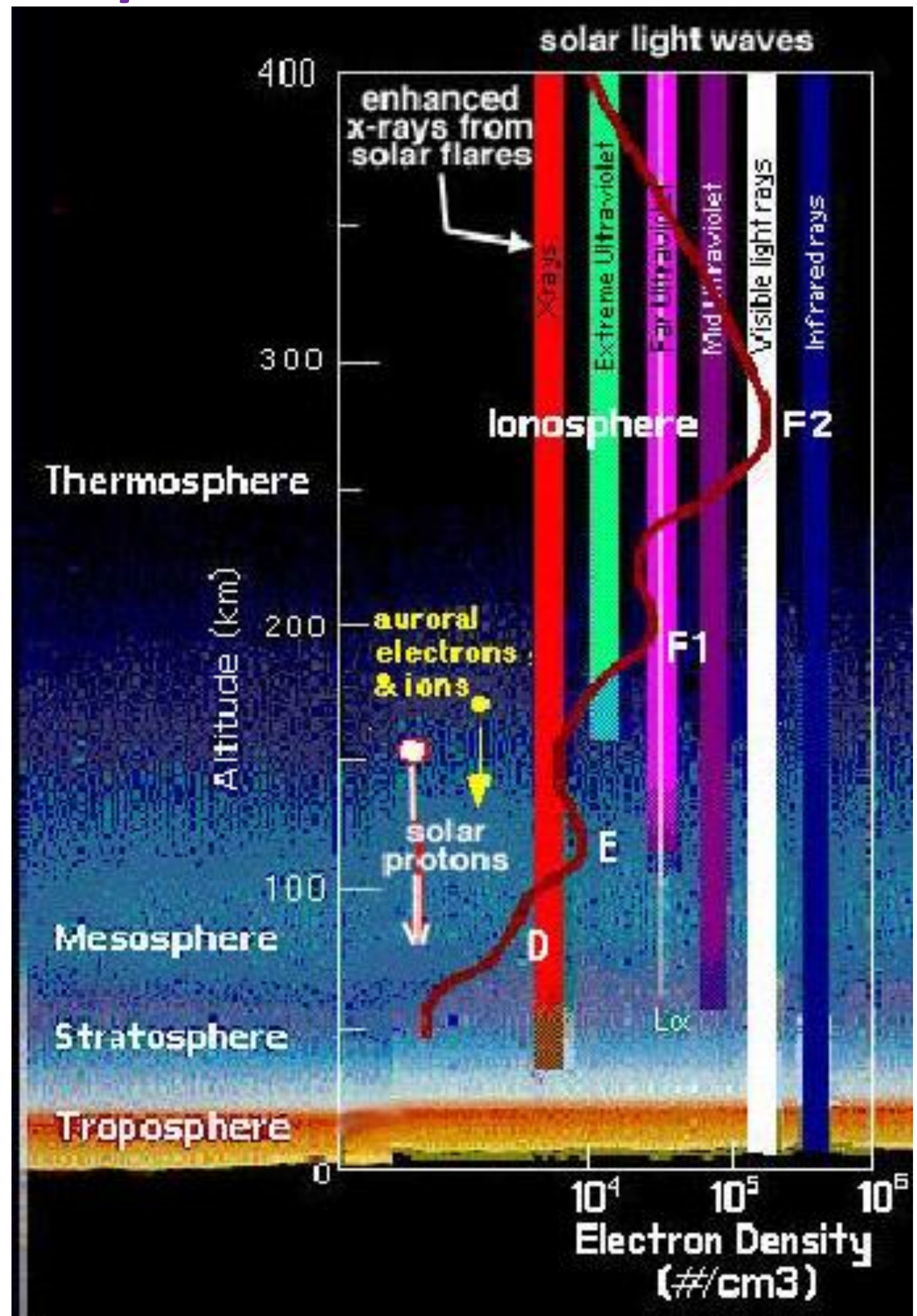
Formation of Ionospheres

Free electrons and positive ions can be formed by

a) photoionization of neutrals

b) energetic particles knocking electrons off neutrals

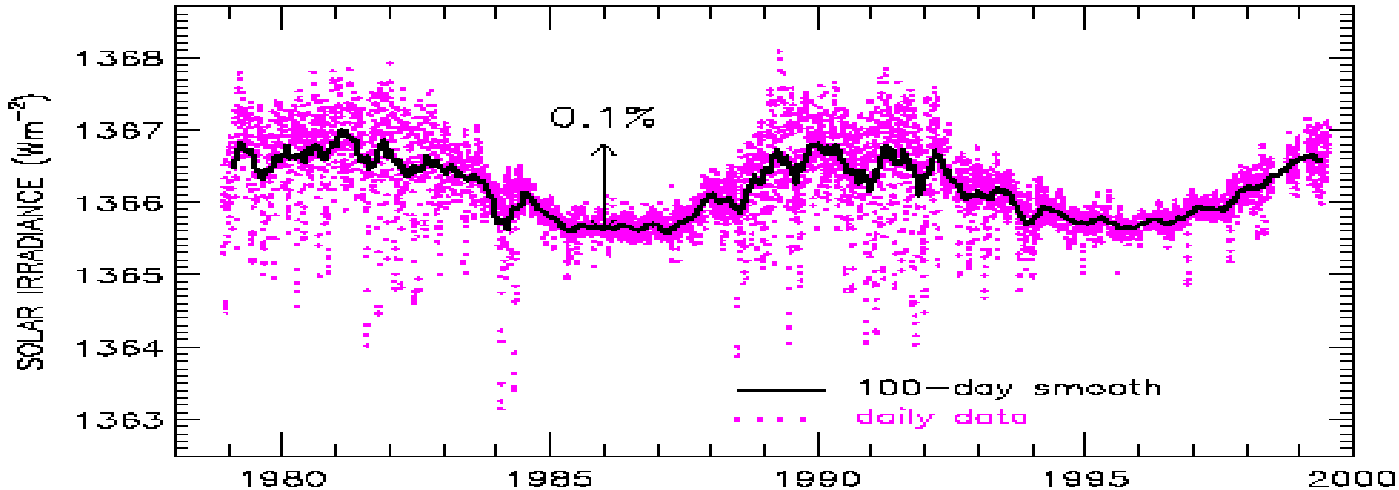




SOLAR - TERRESTRIAL ENERGY SOURCES

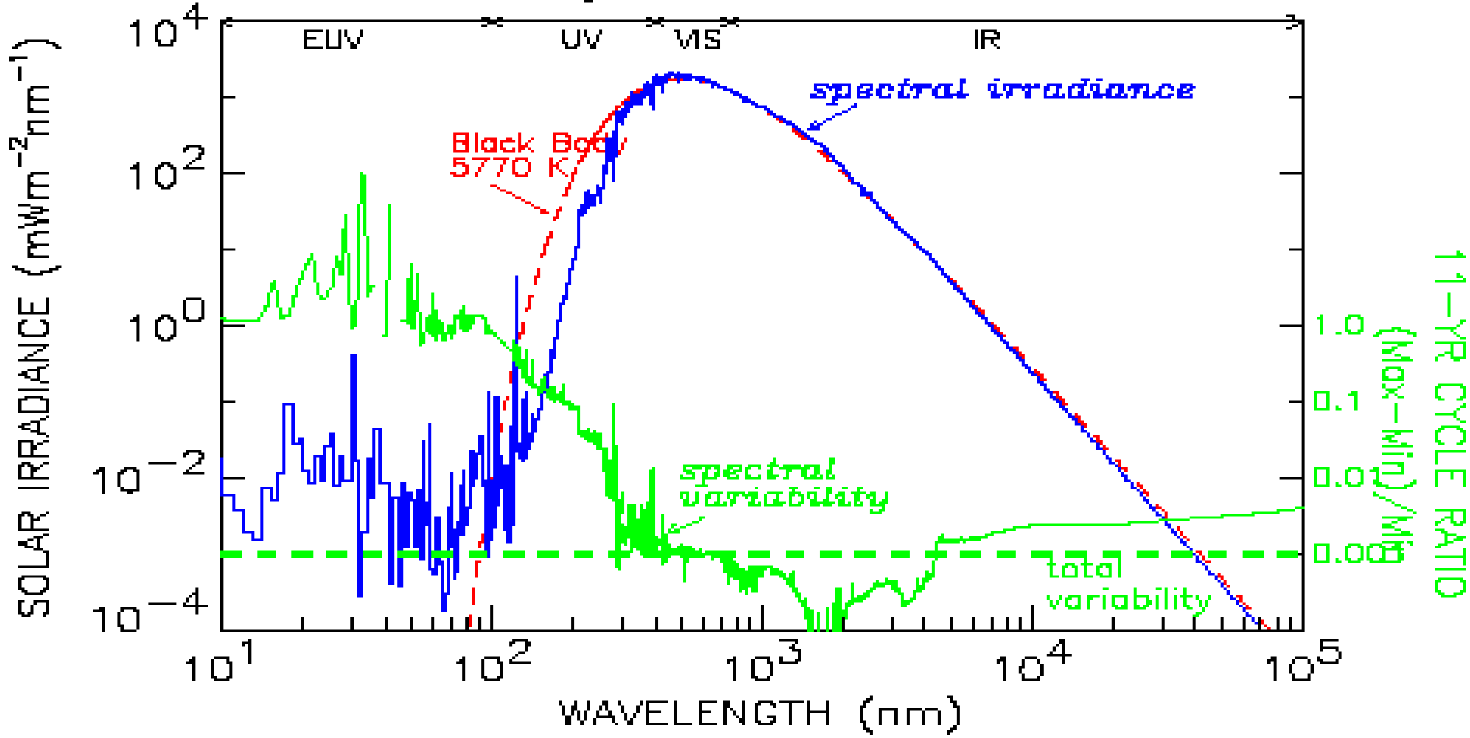
Source	Energy (Wm^{-2})	Solar Cycle Change (Wm^{-2})	Deposition Altitude
Solar Radiation			
• total	1366	1.2	surface
• UV 200-300 nm	15.4	0.17	10-80 km
• VUV 0-200 nm	0.15	0.15	50-500 km
Particles			
• electron aurora III	0.06		90-120 km
• solar protons	0.002		30-90 km
• galactic cosmic rays	0.0000007		0-90 km
Peak Joule Heating (strong storm)			
• $E=180\ mVm^{-1}$	0.4		90-200 km
Solar Wind	0.0006		above 500 km

TOTAL IRRADIANCE VARIABILITY



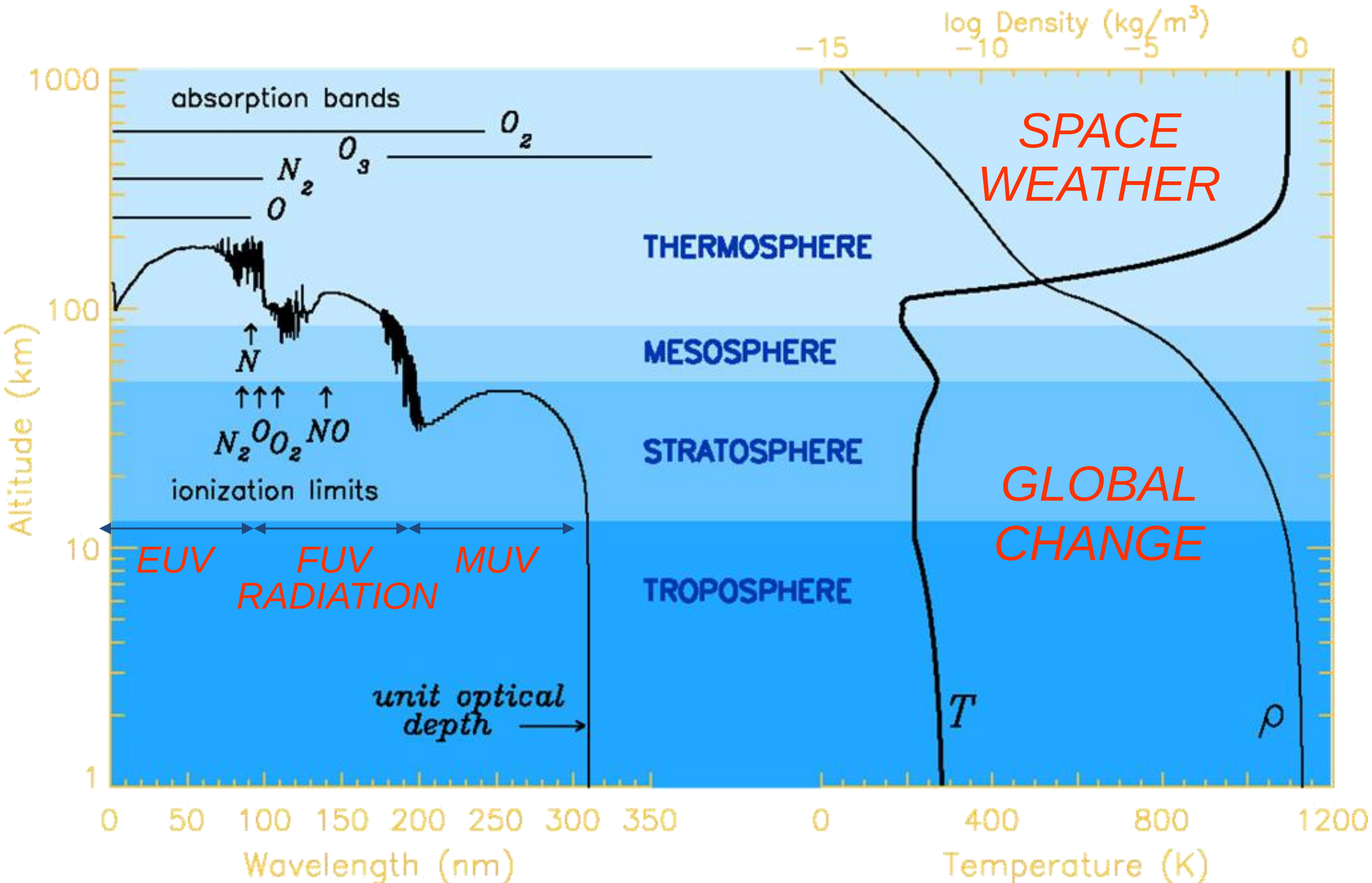
SPECTRUM VARIABILITY

TOTAL Irradiance = $\int$ SPECTRAL Irradiance ~ 1365 Wm^{-2}



Solar Energy Deposition

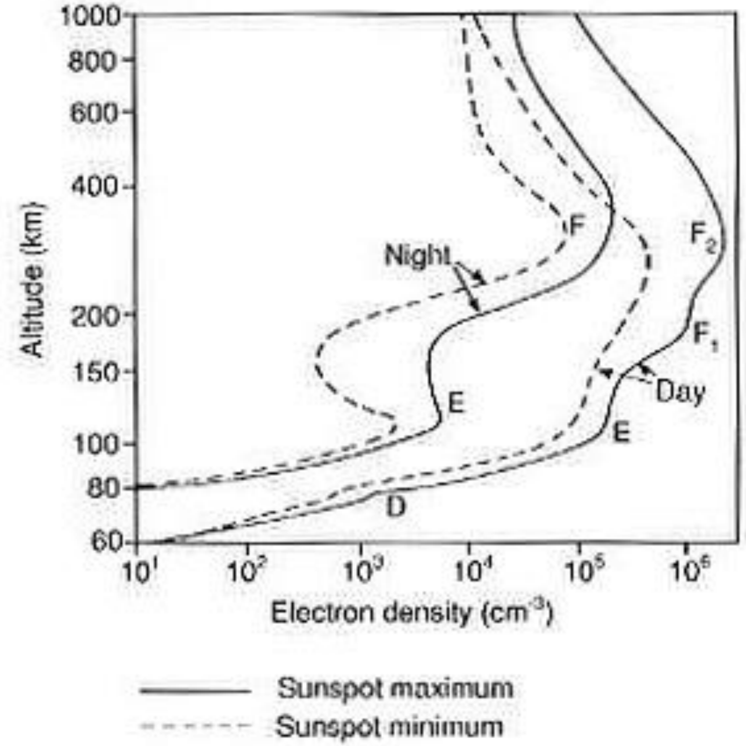
Atmospheric Structure



Atmospheric Absorption Processes

- Ionization
  - $O_2 + h\nu \rightarrow O_2^+ + e^*$, ...
- Dissociation
  - $N_2 + h\nu \rightarrow N + N$, ...
- Excitation
  - $O + h\nu \rightarrow O^*$
    - $O^* \rightarrow O + h\,\nu'$ radiation
    - $O^* + X \rightarrow O + X$ quenching or deactivation
- Dissociative ionization – excitation
  - $N_2 + h\nu \rightarrow N^{+*} + N + e$, ...

The Ionosphere



- There are ions and electrons at all altitudes of the terrestrial atmosphere. Below about 60 km thermal charged particles (which have comparable energies to the neutral gas constituents) do not play any significant role in determining the chemical or physical properties of the atmosphere.

- Above 60 km, the presence of electrons and ions becomes increasingly important. This region of the upper atmosphere is called the ***ionosphere***.

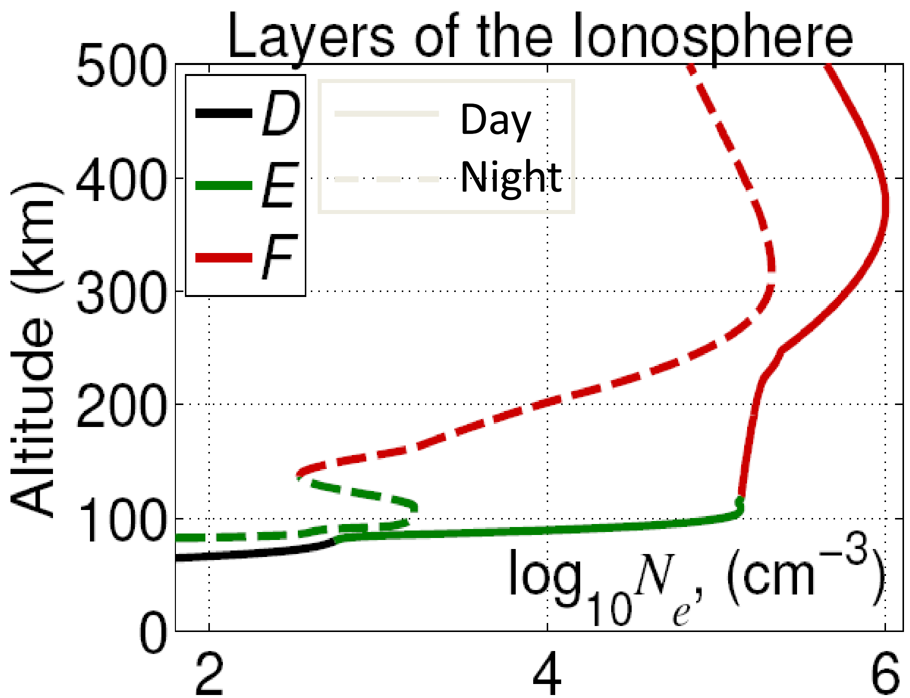
- The typical vertical structure of the ionosphere is shown on top-right: strong diurnal variation and solar cycle variation.

- The identification of the atmospheric layers is usually reflected to inflection points in the vertical density profile: The main regions are local minimums.

- D region (≈60–90 km, peaks around 90 km);
- E region (≈90–140 km, peaks around 110 km);
- F_1 region (≈140–200 km, peaks around 200 km);
- F_2 region (≈200–500 km, peaks around 300 km);
- Topside ionosphere (above the F_2 region).

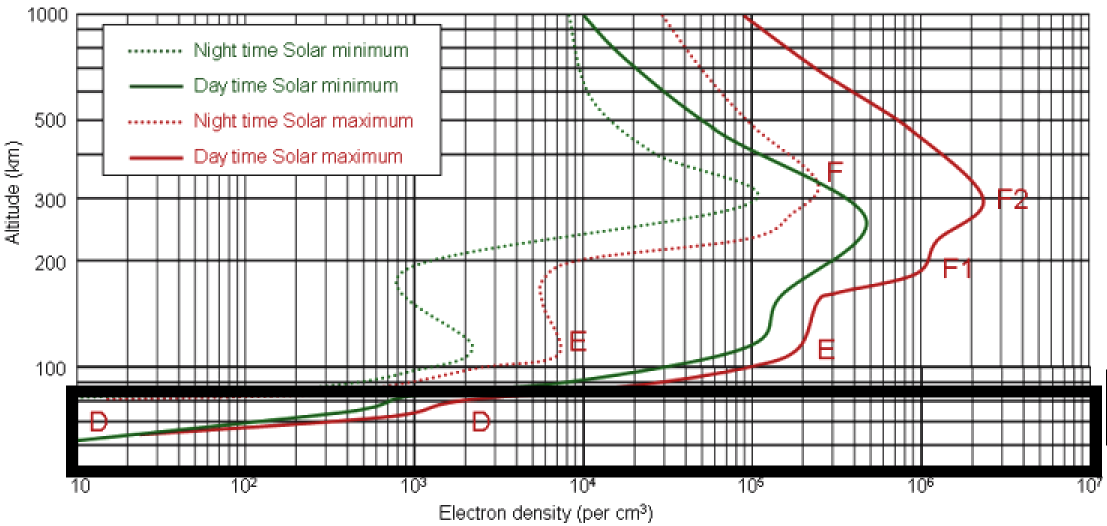
Overview of the Ionosphere

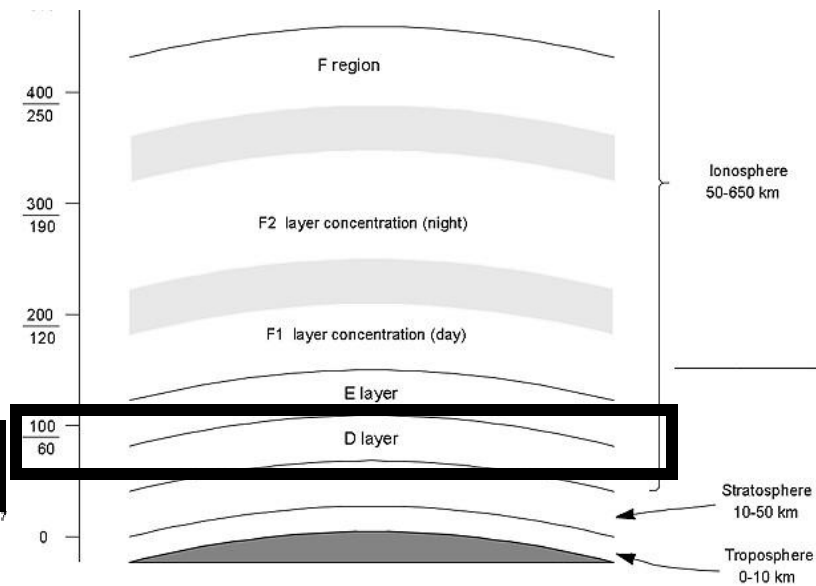
- Structure of ionosphere continuously changing
  - Varies with day/night, seasons, latitude and solar activity
- Essential features are usually identifiable
- Ionosphere divided into layers, according to electron density and altitude
  - D Layer (or D Region)
  - E Layer
  - F Layer
- Several reasons for distinct layers
  - Solar spectrum energy deposited at various altitudes depending on absorption of atmosphere
  - Physics of recombination depends on density of atmosphere (which changes with altitude)
  - Composition of atmosphere changes with height



Ionospheric Layers

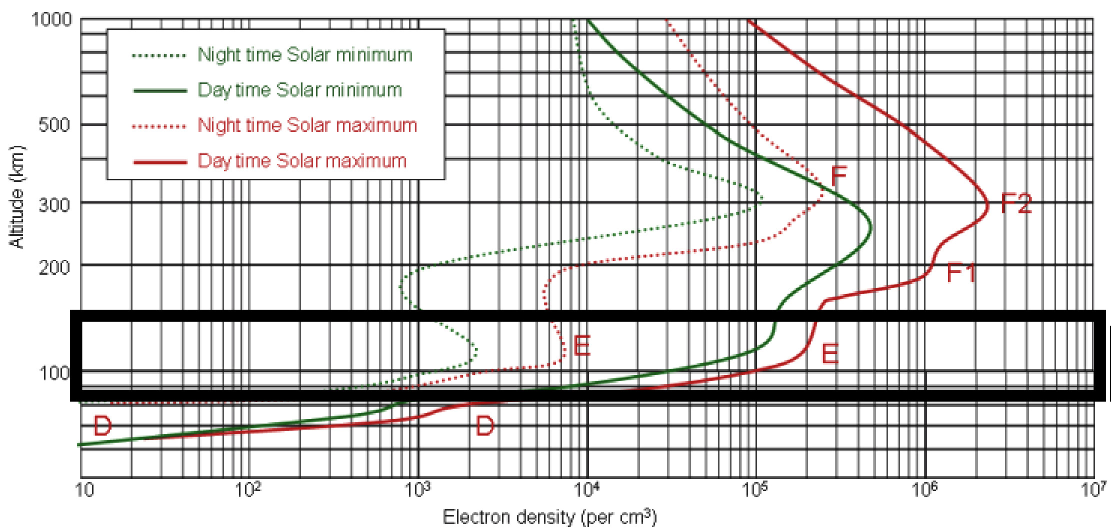
- D region (50-90 km)
  - Lowest region, produced by Lyman series alpha radiation (λ = 121.6 nm) ionizing Nitric Oxide (NO)
  - Very weakly ionized
    - Electron densities of $10^8 – 10^{10}$ e^-/m^3 during the day
  - At night, when there is little incident radiation (except for cosmic rays), the D layer mostly disappears except at very high latitudes

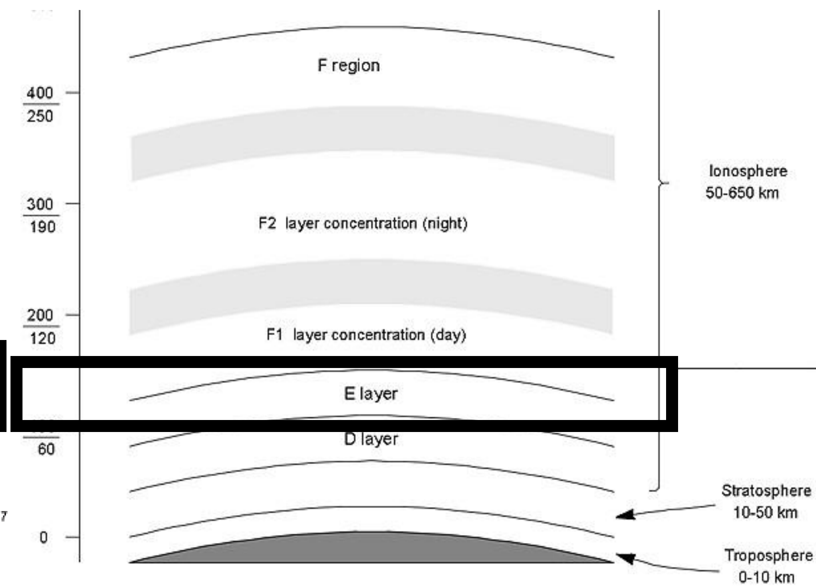




Ionospheric Layers

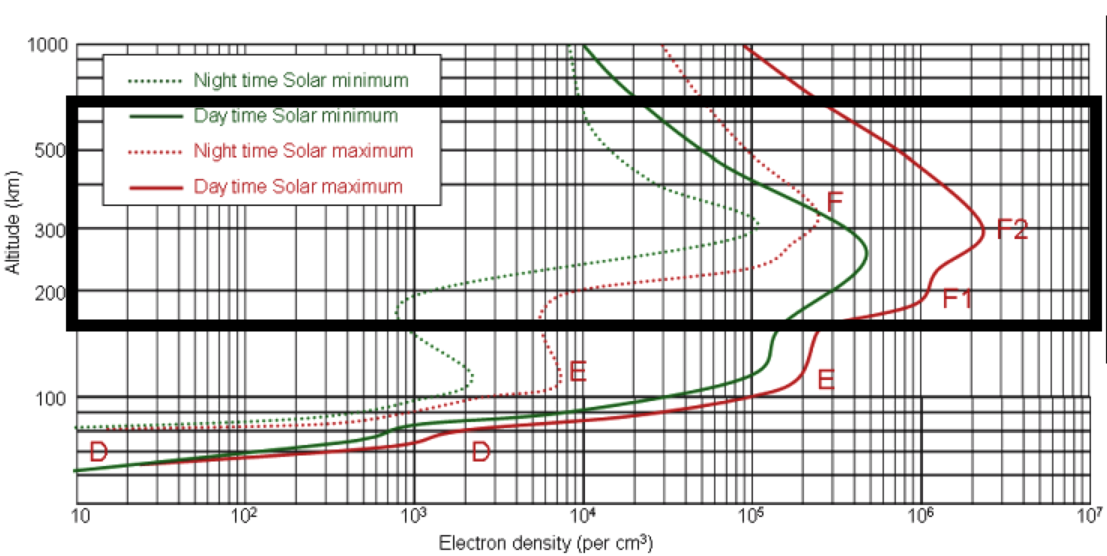
- E Region (90-140 km)
  - Produced by X-ray and far ultraviolet radiation ionizing molecular oxygen (O_2)
  - Daylight maximum electron density of about 10^{11} e^{-}/m^{3}
    - Occurs at ~100km
  - At night the E layer begins to disappear due to lack of incident radiation
    - This results in the height of maximum density increasing

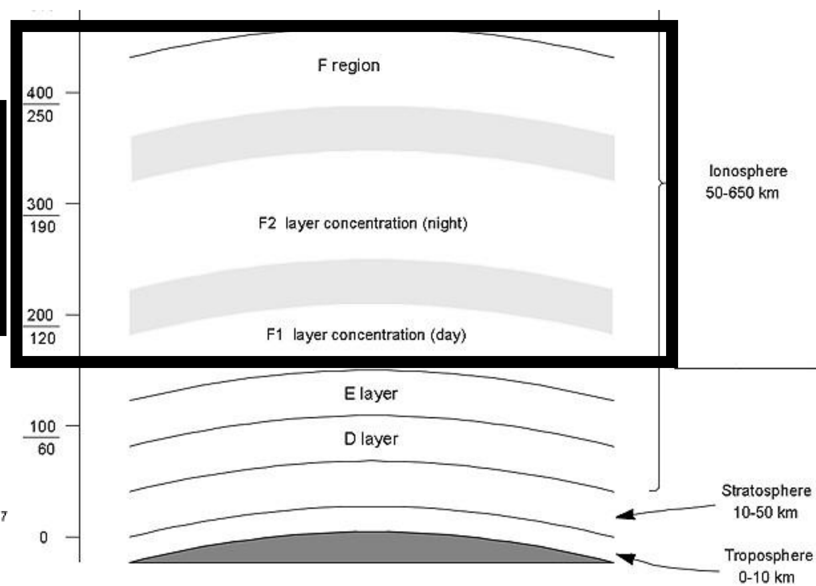




Ionospheric Layers

- F1 Layer (140-200km)
  - Electron density ~$3*10^{11}$ e^-/m^3
  - Caused by ionization of atomic Oxygen (O) by extreme ultraviolet radiation (10-100nm)
- F2 Layer (>200km)
  - Usually has highest electron density (~$2*10^{12}$ e^-/m^3)
  - Consists primarily of ionized atomic Oxygen (O^+) and Nitrogen (N^+)

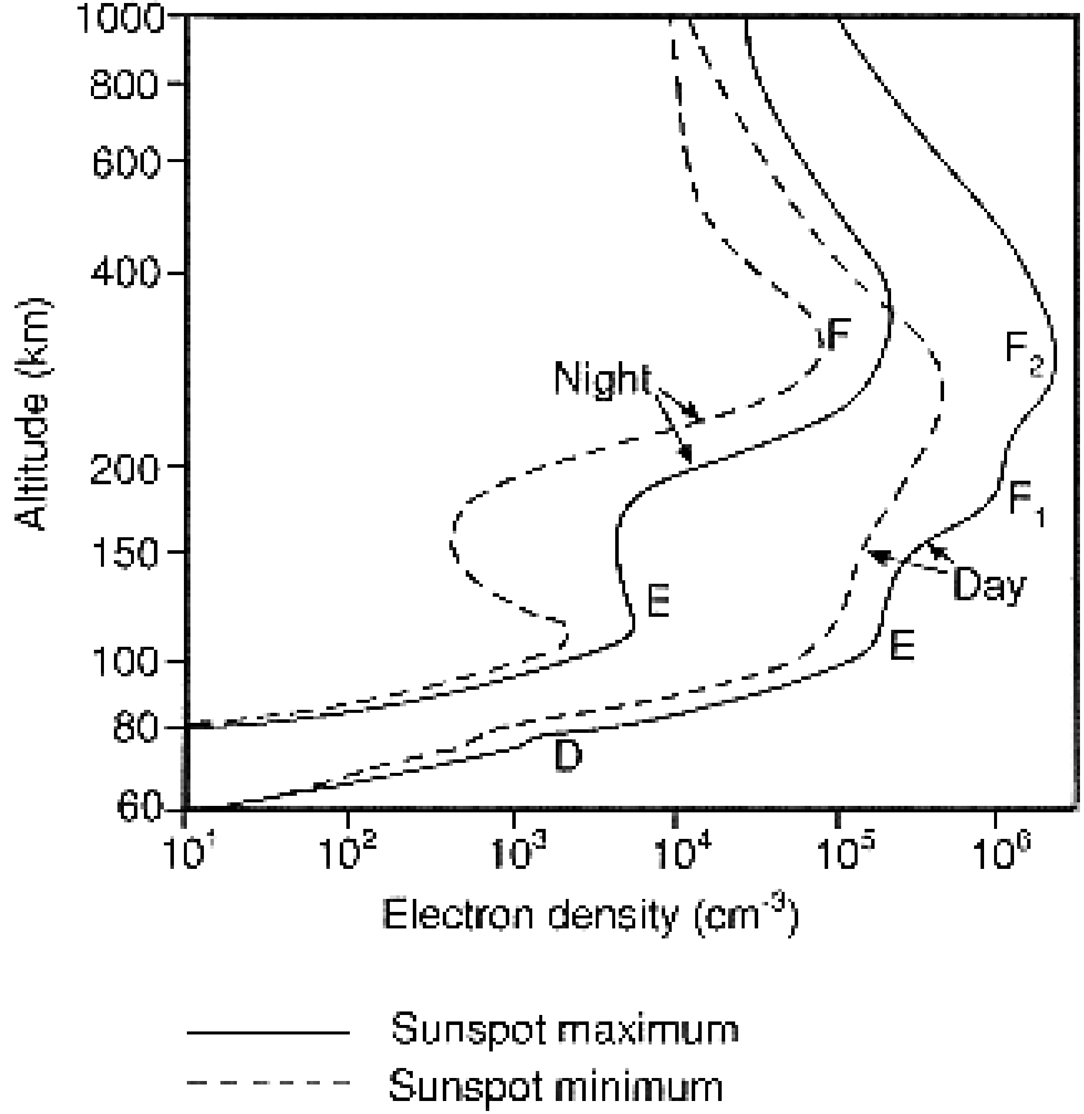




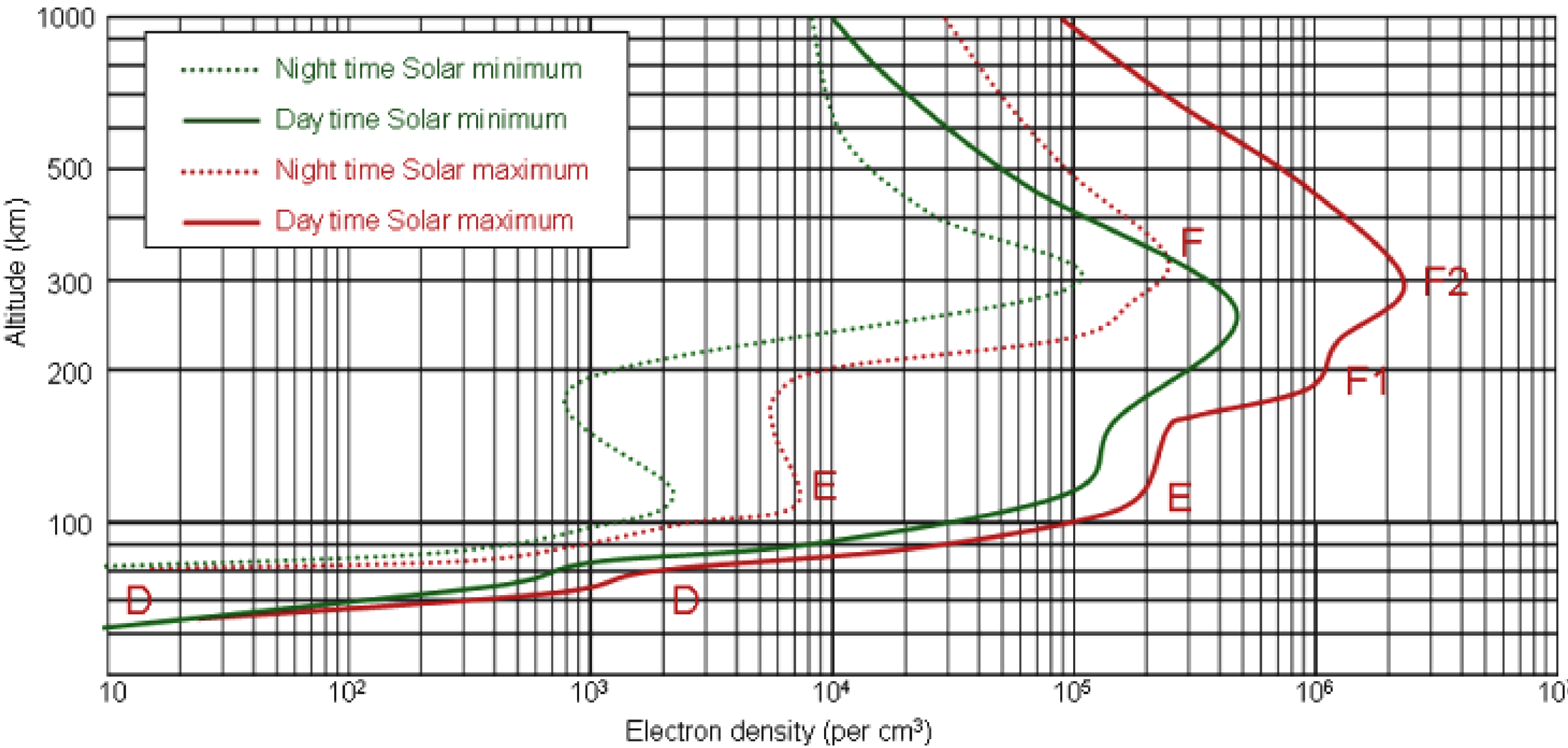
Primary Ionospheric Regions			
Region	Altitude	Peak	Density
D	60-90 km	90 km	10^8 –10^{10} m^{-3}
E	90-140 km	110 km	Several x 10^{11} m^{-3}
F1	140-200 km	200 km	Several 10^{11}-10^{12} m^{-3}
F2	200-500 km	300 km	Several x 10^{12} m^{-3}
Topside	above F2		

Diurnal and Solar Cycle Variations

- In general densities are larger during solar maximum than during solar minimum.
- The D and F_1 regions disappear at night.
- The E and F_2 regions become much weaker.
- The topside ionosphere is basically an extension of the magnetosphere.



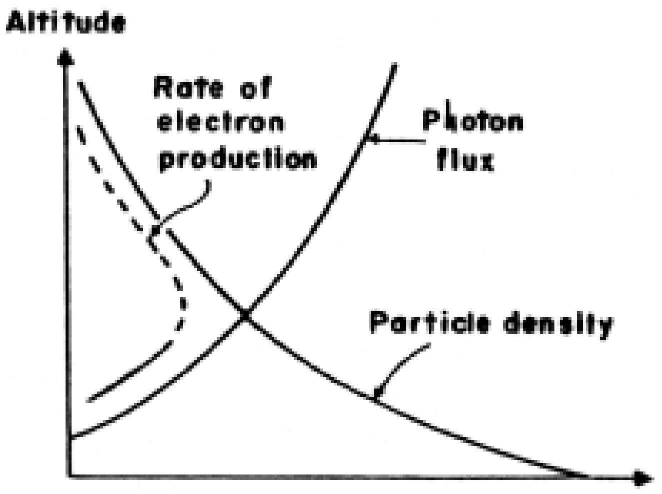
Solar Activity Variations



Ionization of the Atmosphere

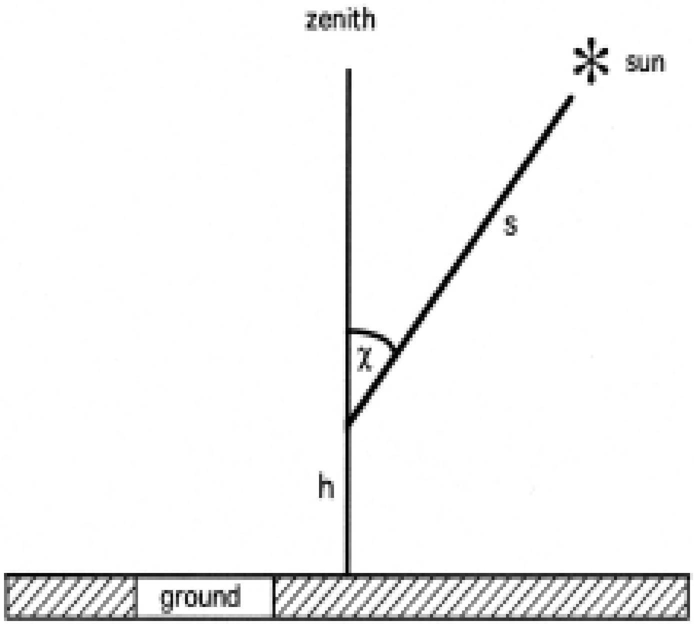
- Formation of layers can be understood by considering ionization of any molecule (or atom) B in the atmosphere
  - $B + hf \rightarrow B^+ + e^-$
  - Rate of this reaction will depend on concentration of molecules B and photons *hf*

- **At high altitudes there are many photons, but few particles**
- **At low altitudes there are many particles but few photons of sufficient energy to cause ionization**



Chapman Layers

- Sydney Chapman used several assumptions to develop a simplified theoretical model
  - Atmosphere consists of only one gas
  - Radiation from the sun is monochromatic
  - Atmospheric density decreases exponentially with height
  - Solar radiation is attenuated exponentially
  - Earth is flat (In order to simplify geometry)
- Each atmospheric species has its own ionization potential and reaction rate
  - Ionosphere can be modeled as superposition of simple Chapman layers



Chapman Geometry

Chapman Layer

- The Chapman profile of an ionospheric layer results from the superposition of the height dependence of the particle density and the flux of the ionizing electromagnetic radiation

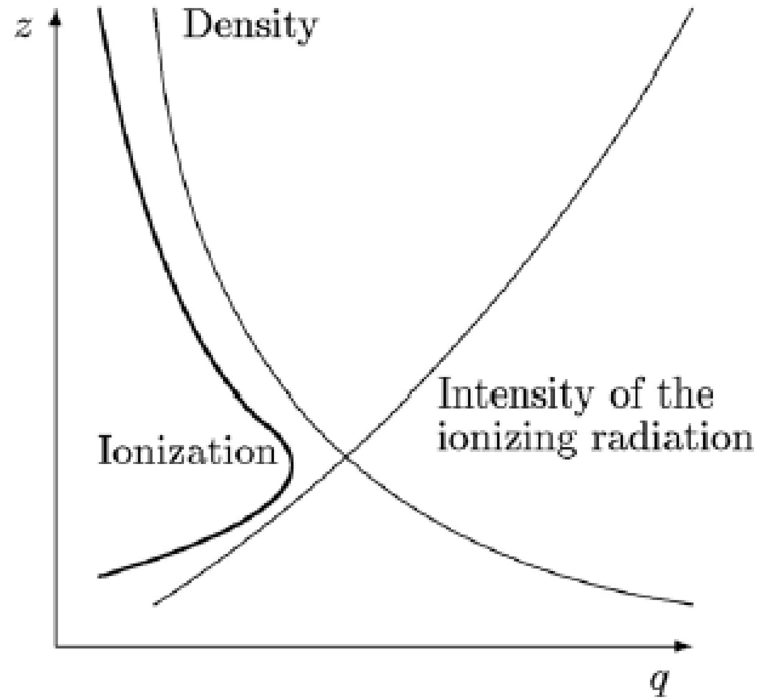
$$q(z) = n\sigma_i I(z)$$

q : ionization rate

n : neutral particle density

σ_i : ionization cross section

I : radiation intensity



Chapman Profile

Chapman Layer

- **Neutral particle density: barometric height formula**

$$n(z) = n_0 \exp\{-\frac{z}{H}\}$$

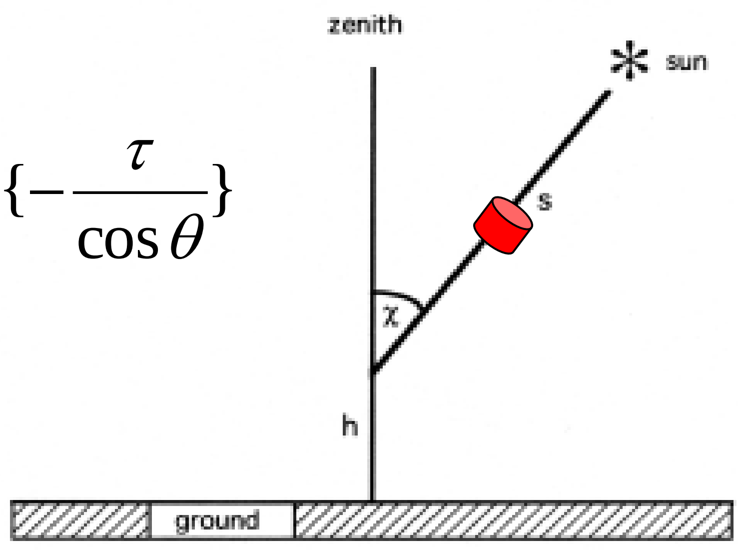
- **Radiation Intensity: Bougert-Lambert-Beer’s Law**

$$\frac{dI}{dz} = -I_\infty \sigma_a n$$

$$I(z) = I_\infty \exp\{-\frac{1}{\cos\theta}\int_z^\infty \sigma_a n(z)dz\} = I_\infty \exp\{-\frac{\tau}{\cos\theta}\}$$

θ : the Sun's altitude. The optical depth τ

$$\tau = \int_z^\infty \sigma_a n(z)dz$$



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*)

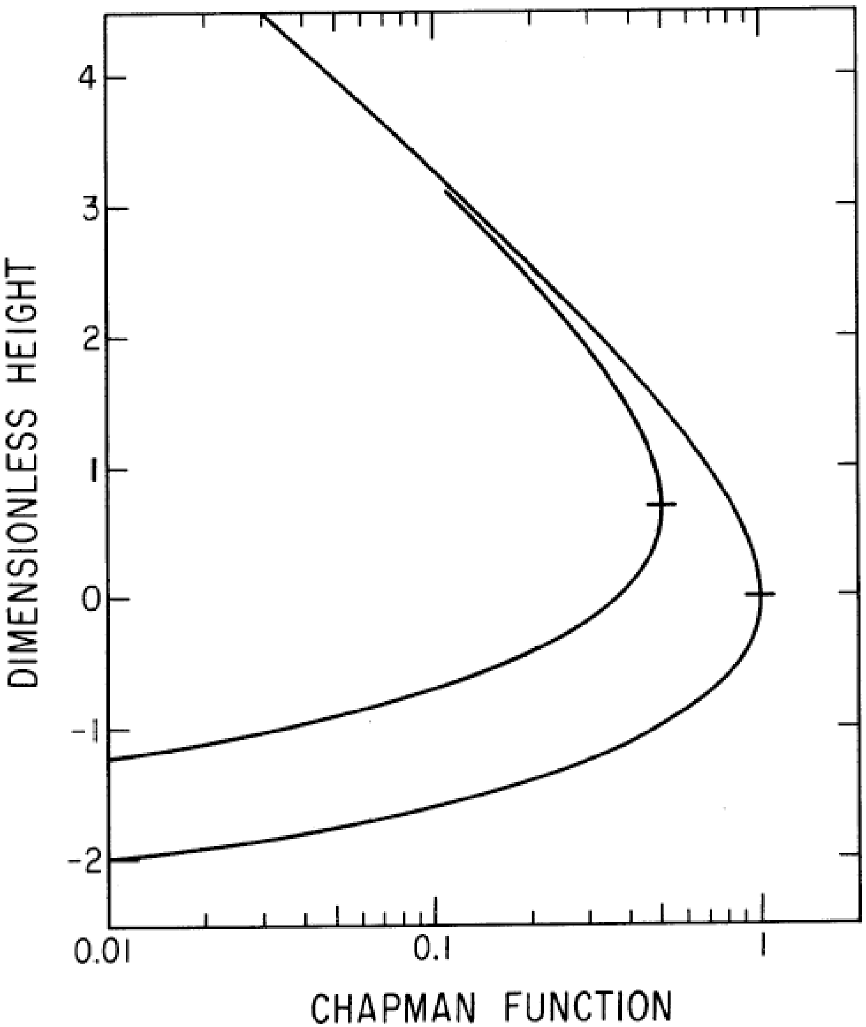
$$I_z = I_\infty \exp\left[-\frac{\sigma n_0 H}{\mu} \exp\left(-\frac{z - z_0}{H}\right)\right]$$

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?

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

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

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

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

$$\tau_z = 1$$

Why is Study of the Ionosphere Important?

- It affects all aspects of radio wave propagation on earth, and any planet with an atmosphere
- Knowledge of how radio waves propagate in plasmas is essential for understanding what’s being received on an AWESOME setup
- It is an important tool in understanding how the sun affects the earth’s environment

Ionospheric Variability

External Sources:

(1) Solar Radiation (X-ray and UV): solar cycle, seasonal, solar rotation, solar flares.

(2) Solar Wind (velocity, density, IMF, energetic particles): solar cycle, seasonal, solar rotation, CMEs and solar flares.

(3) Solar and Lunar Tides

Internal Sources:

(1) Earth's rotations ➔ Circulation, Convection, Turbulences.

(2) Earth's magnetic field ➔ interaction with solar wind, charged particle's motions.

(3) Earth's Ion compositions ➔ productions and recombination.

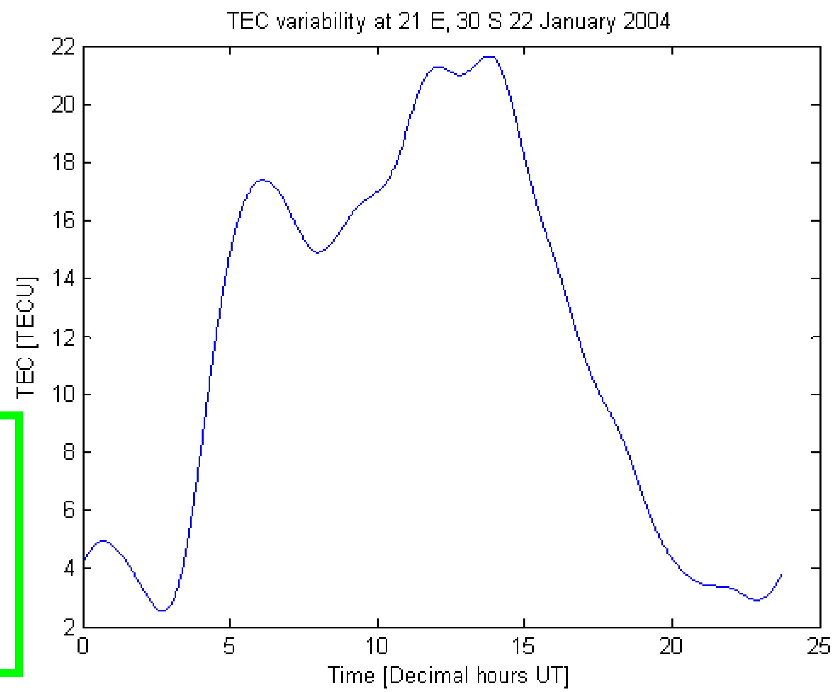
Variation of Ion Density

- The ionization production depends on the solar radiation intensity and the zenith angle
- The ion density shows daily, seasonal variation as well solar rotation and solar cycle effects

After sunrise

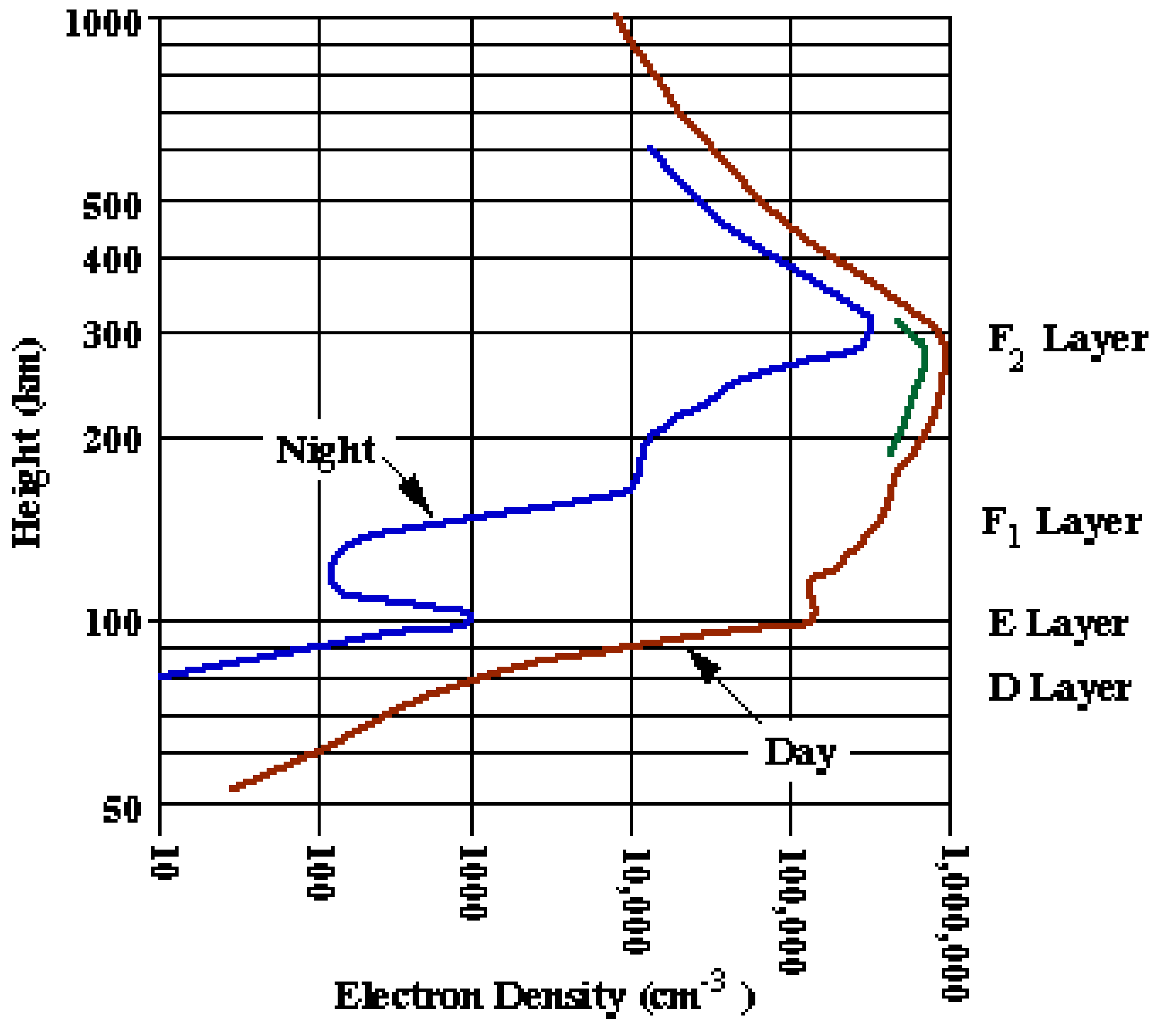
$$\frac{\partial n}{\partial t} \approx 10^8 m^{-3} s^{-1}$$

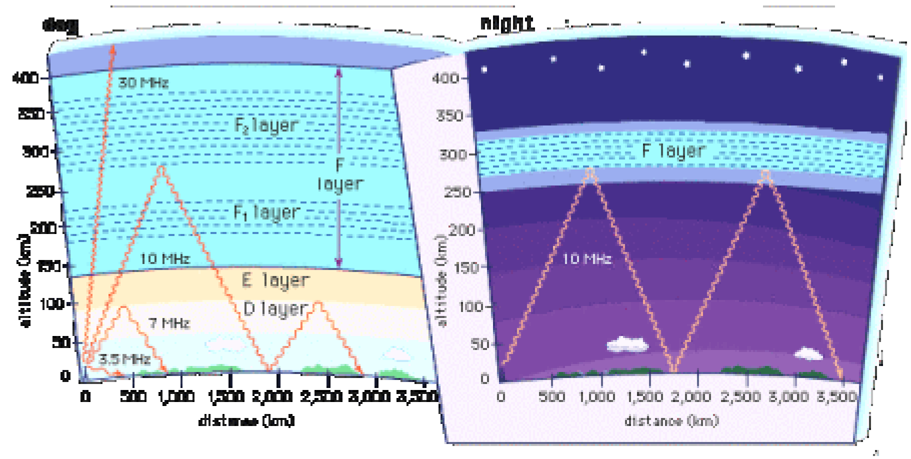
TEC (Total Electron Content) diurnal variation



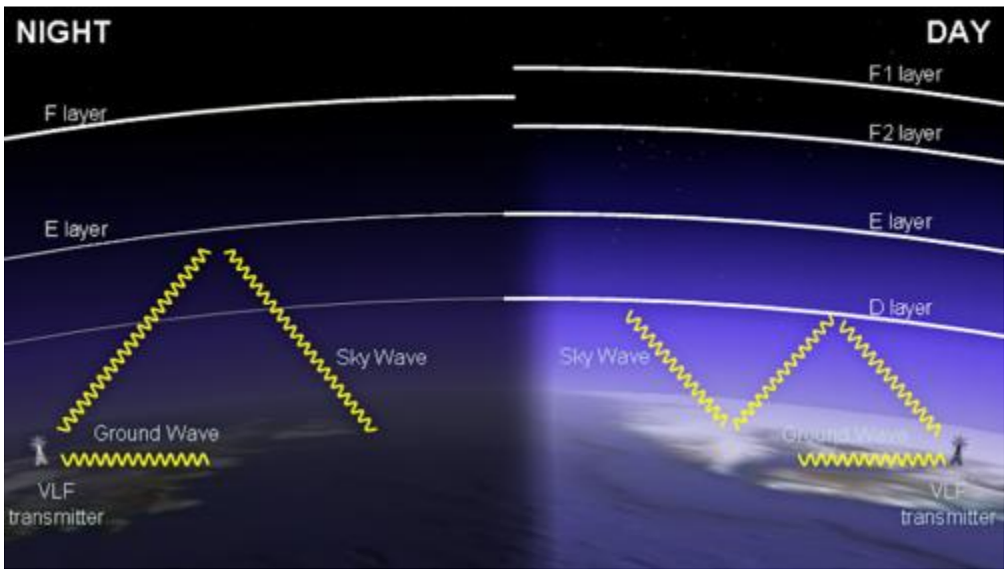
Variation of Ion Density

D and F1-layers may disappear at night

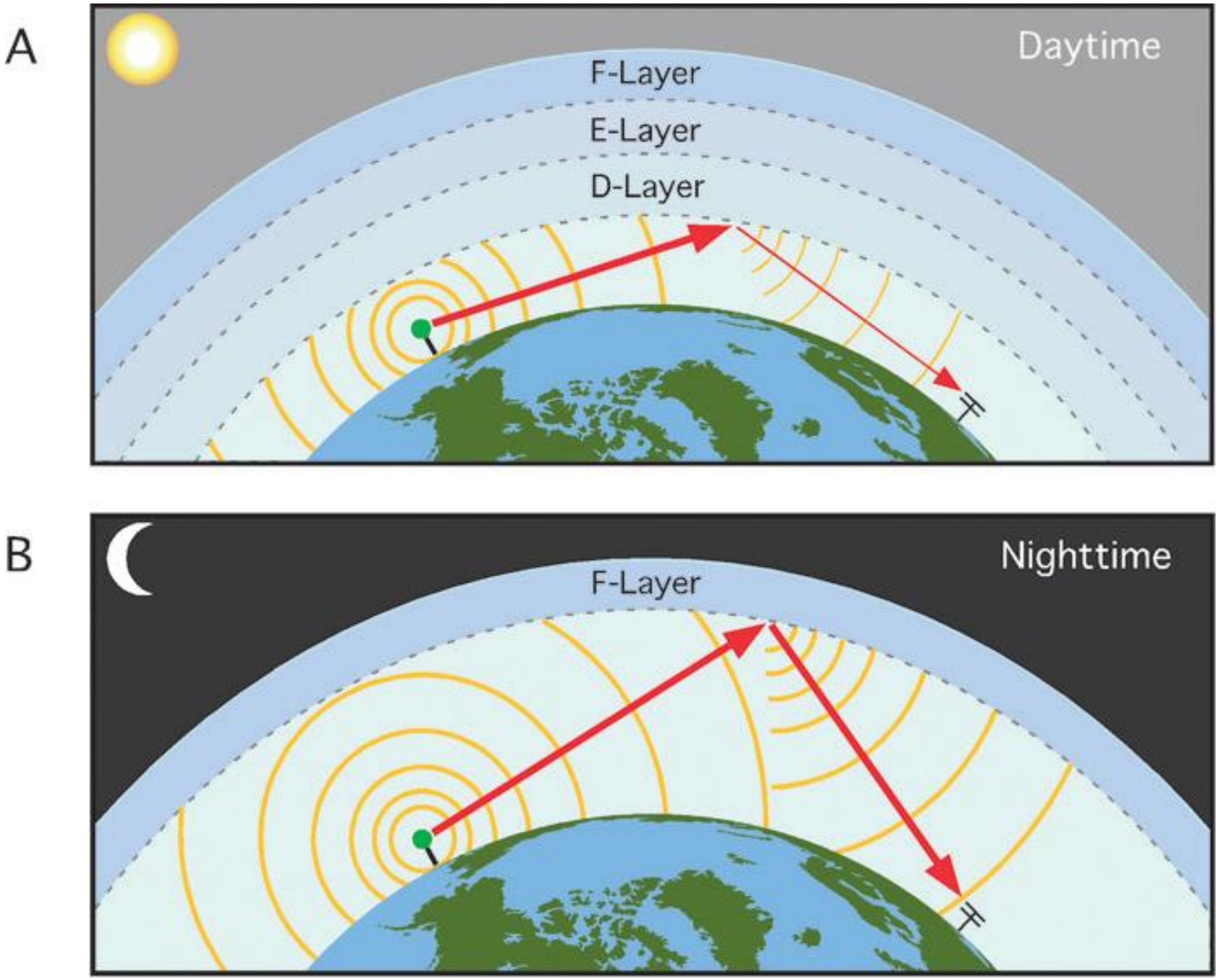




day
night
30 MHz
F2 layer
F layer
F1 layer
10 MHz
E layer
D layer
7 MHz
3.5 MHz
altitude (km)
distance (km)
F layer
10 MHz
altitude (km)
distance (km)



NIGHT
DAY
F layer
F1 layer
F2 layer
E layer
E layer
D layer
Sky Wave
Sky Wave
Ground Wave
VLF transmitter
VLF transmitter


A
Daytime
F-Layer
E-Layer
D-Layer
B
Nighttime
F-Layer

The Sky Above