# Earth's Atmosphere

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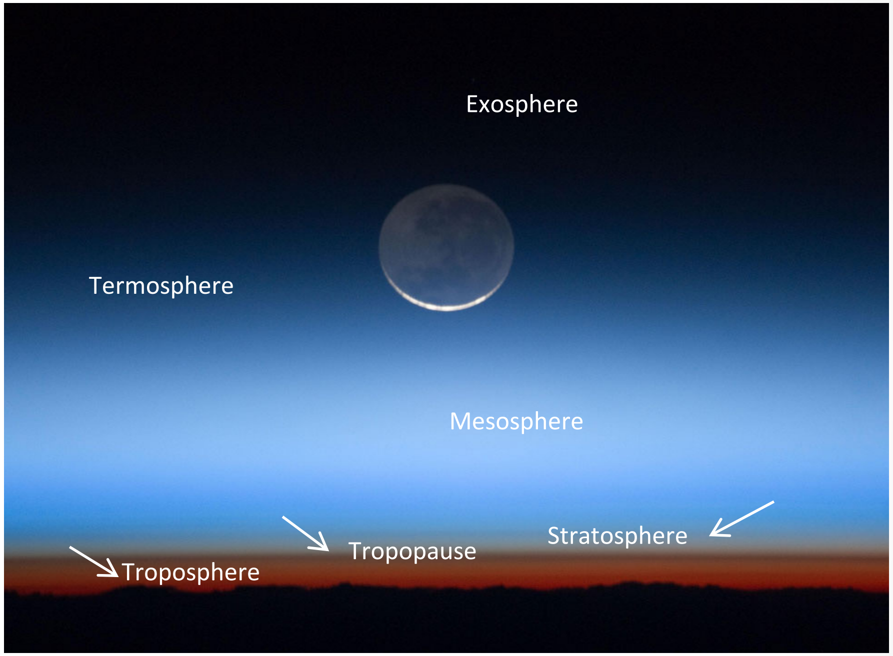
# Summary

- Neutral atmosphere
- Atmospheric retention
- Ozone layer
- Atmospheric measures
- Ionosphere

# What is the atmosphere?

Mixture of invisible permanent and variable gases as well as suspended microscopic particles (both liquid and solid)

- Permanent Gases – Form a constant proportion of the total atmospheric mass
- Variable Gases – Distribution and concentration varies in space and time
- Aerosols – Suspended particles and liquid droplets (excluding cloud droplets)




**Limb of the Earth**: On July 31, 2011, astronauts on the International Space Station captured this image of the earth's atmosphere and the crescent moon. Though the Moon is more than 384,400 kilometers (238,855 miles) away, the perspective from the camera makes it appear to be part of our atmosphere. *Image credit: NASA*

# Composition of Earth's Atmosphere

permanent gases remain constant up to 80-100km high

Important gases in the Earth's Atmosphere (Note: Influence not necessarily proportional to % by volume!)

•TABLE 1.1

**Composition of the Atmosphere Near the Earth's Surface**

| PERMANENT GASES | | | VARIABLE GASES | | | |
|---|---|---|---|---|---|---|
| Gas | Symbol | Percent (by Volume) Dry Air | Gas (and Particles) | Symbol | Percent (by Volume) | Parts per Million (ppm)* |
| Nitrogen | $N_2$ | 78.08 | Water vapor | $H_2O$ | 0 to 4 | |
| Oxygen | $O_2$ | 20.95 | Carbon dioxide | $CO_2$ | 0.038 | 380* |
| Argon | Ar | 0.93 | Methane | $CH_4$ | 0.00017 | 1.7 |
| Neon | Ne | 0.0018 | Nitrous oxide | $N_2O$ | 0.00003 | 0.3 |
| Helium | He | 0.0005 | Ozone | $O_3$ | 0.000004 | 0.04† |
| Hydrogen | $H_2$ | 0.00006 | Particles (dust, soot, etc.) | | 0.000001 | 0.01–0.15 |
| Xenon | Xe | 0.000009 | Chlorofluorocarbons (CFCs) | | 0.00000002 | 0.0002 |

*For $CO_2$, 380 parts per million means that out of every million air molecules, 380 are $CO_2$ molecules.

†Stratospheric values at altitudes between 11 km and 50 km are about 5 to 12 ppm.

# Neutral atmospheric layers

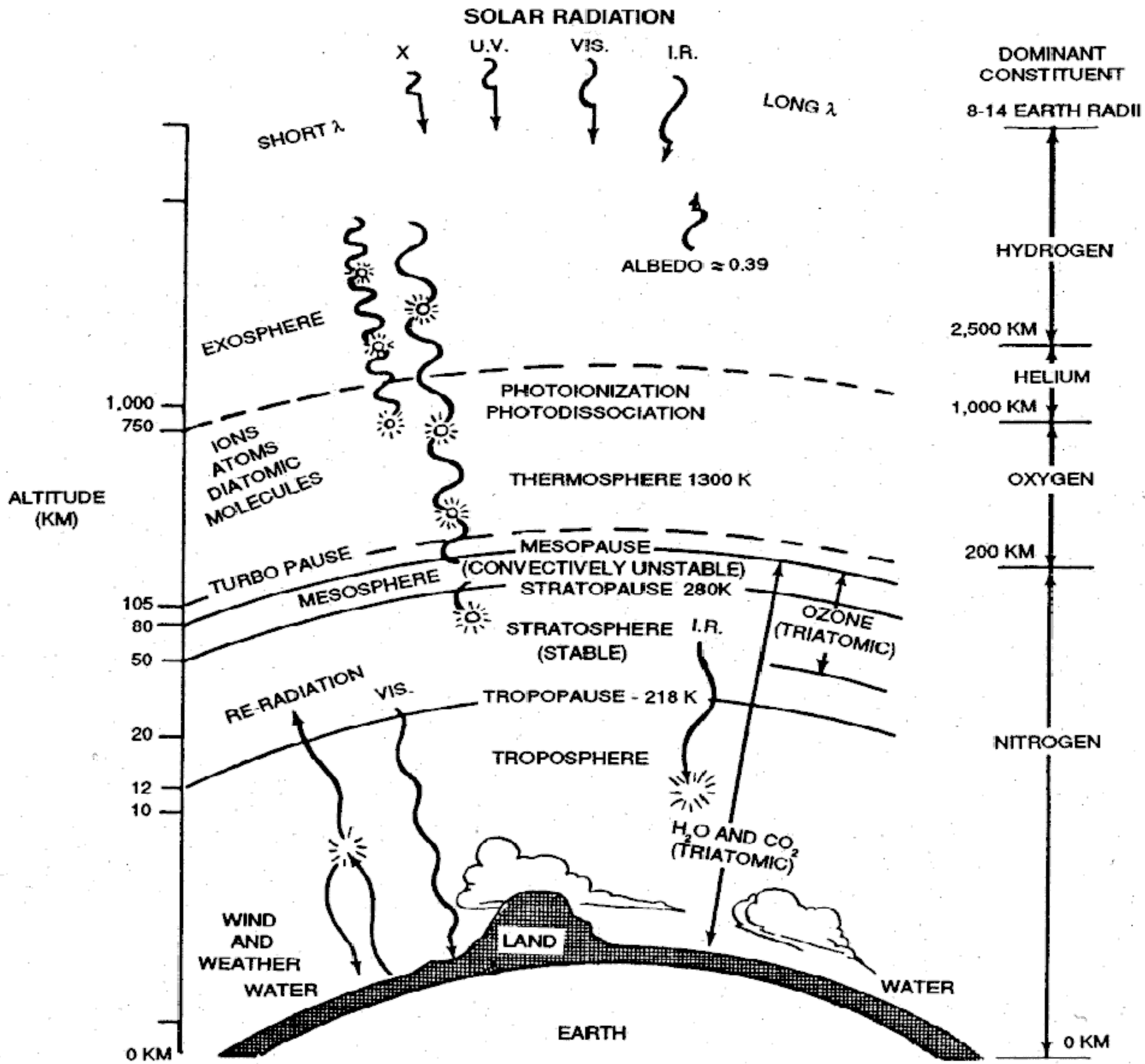
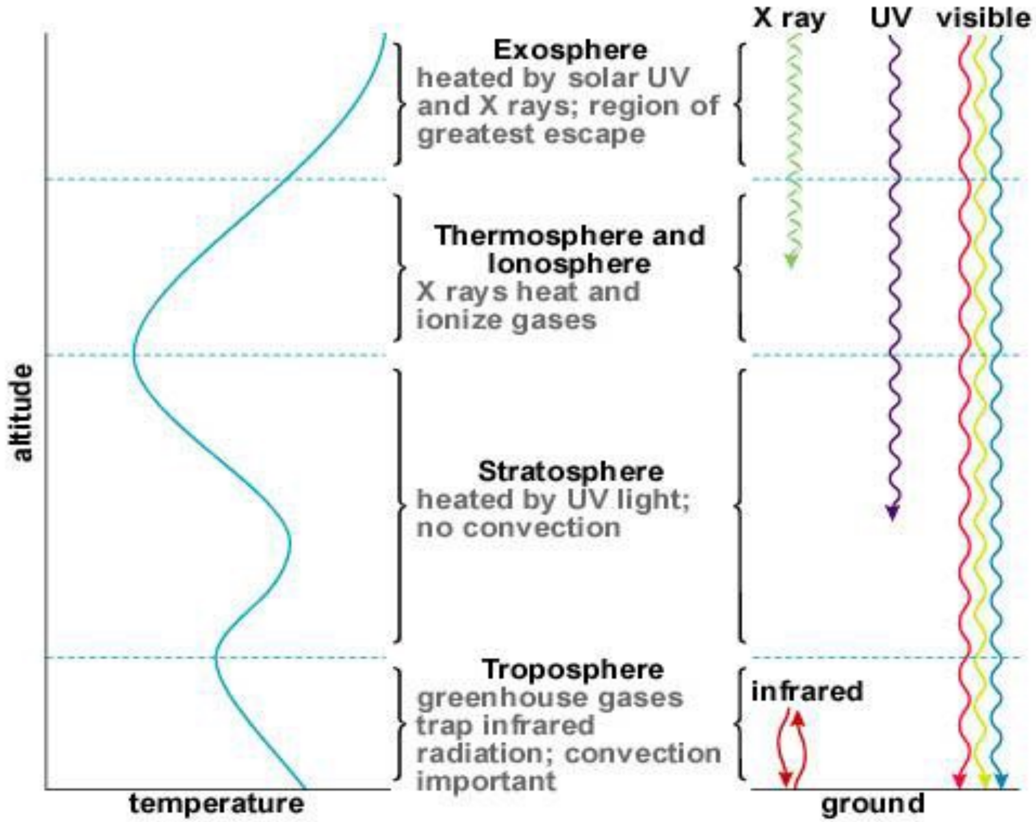


**Figure 6.2** Atmospheric chemical regimes *(after Carpenter et al., 1978).*

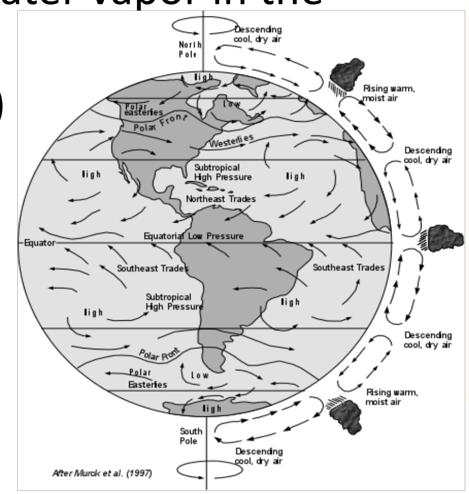
# Neutral atmospheric layers

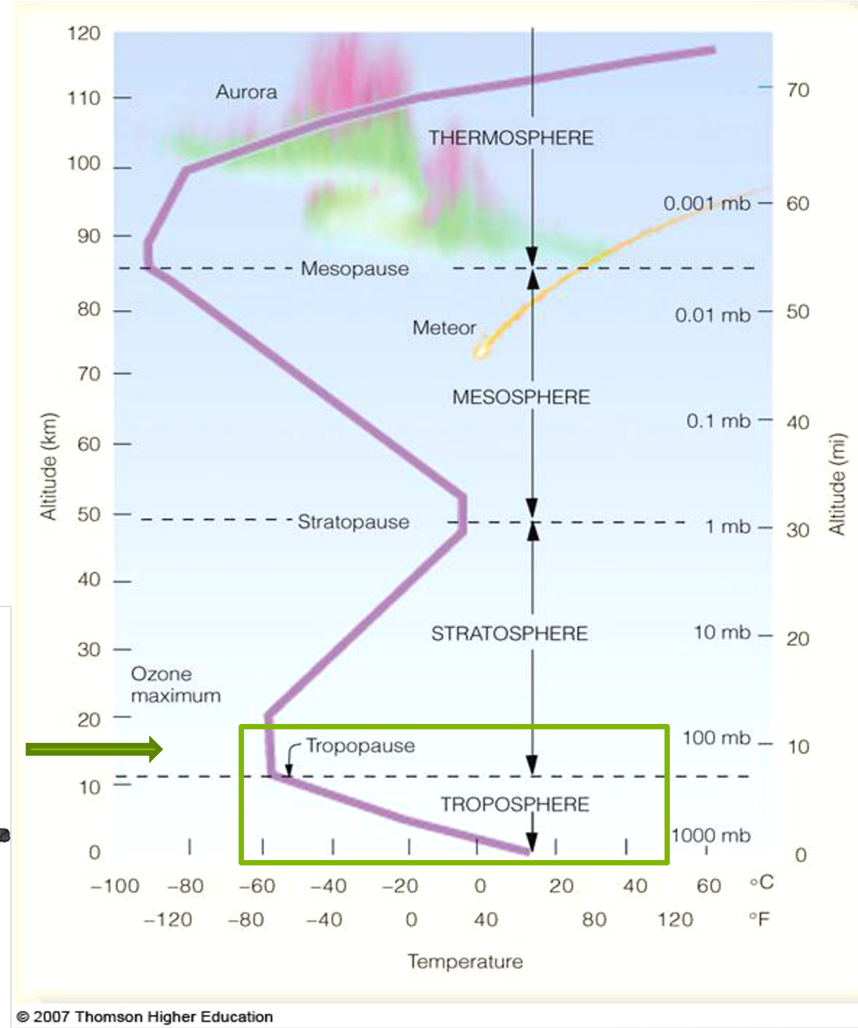


# Neutral atmospheric layers

## TROPOSPHERE

- Lower part of the atmosphere (0 -10 km)
- Contains 80% of the mass of the total atmosphere ($O_2$, $N_2$, $H_2O$,…)
- Energy source is heating of the earth's surface by the sun
- Temperature generally decreases with height (- 6.5°C/km)
- It contains 99 % of the water vapor in the atmosphere
- Air circulations (weather)

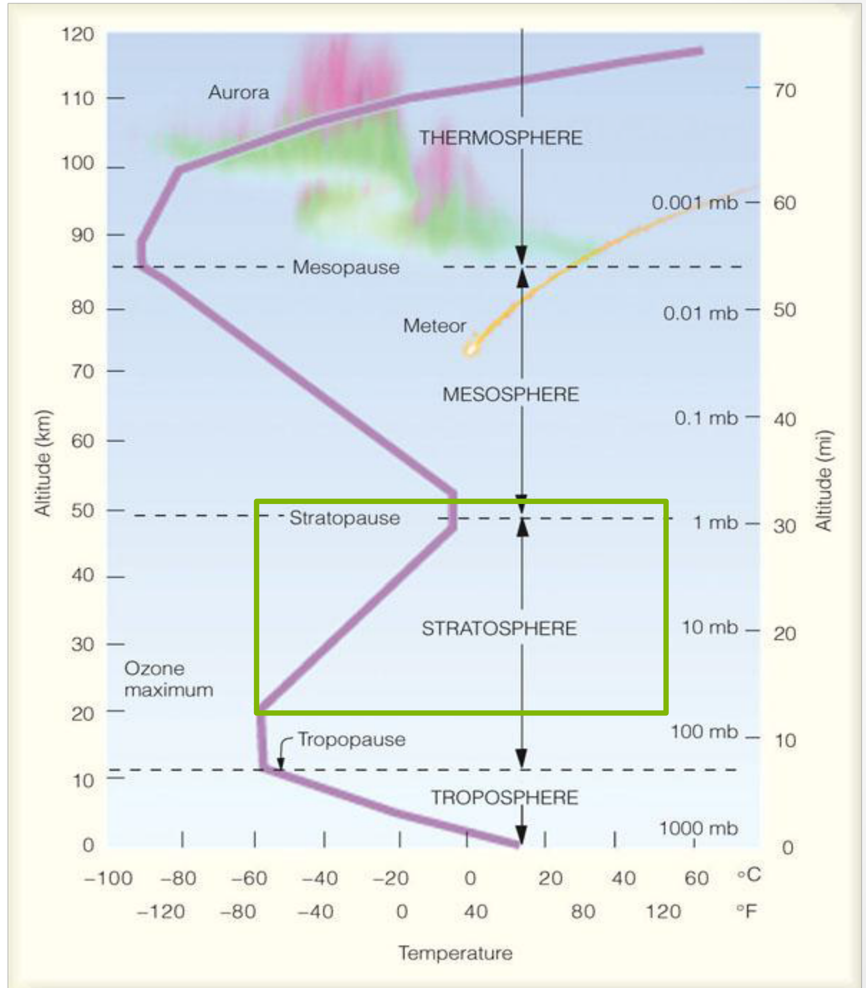


# Neutral atmospheric layers

## STRATOSPHERE

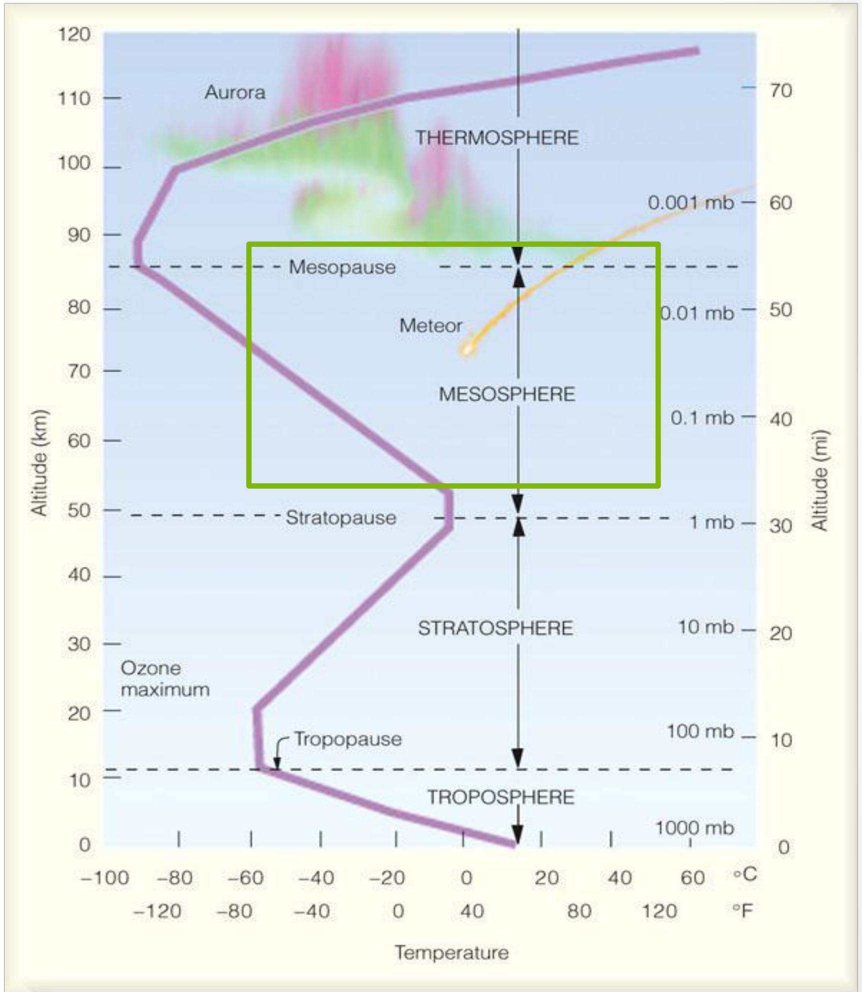
- From about 10 to 50 km above the surface
- Sun's UV light is absorbed by ozone ($O_3$), heating the air.
- Heating causes increase of temperature with height.
- Boundary between troposphere and stratosphere is the stratopause.



# Neutral atmospheric layers

## MESOSPHERE

- From about 50 km to 90 km above the surface
- Above 50 km, very little ozone, so no solar heating ➡ Air continues to cool with height in mesosphere
- Same altitude as the turbopause
- Difficult to study
- Noctilucent clouds



# Neutral atmospheric layers

THERMOSPHERE

- Above 90 km to 500 – 1000 km (depending on solar activity)
- Absorbed energy causes increase of temperature with height (EUV, x-rays, $\gamma$ - rays)
- This layer is completely cloudless and free of water vapor
- Extremely low density (L ~ 1.6 km)
- Aurora

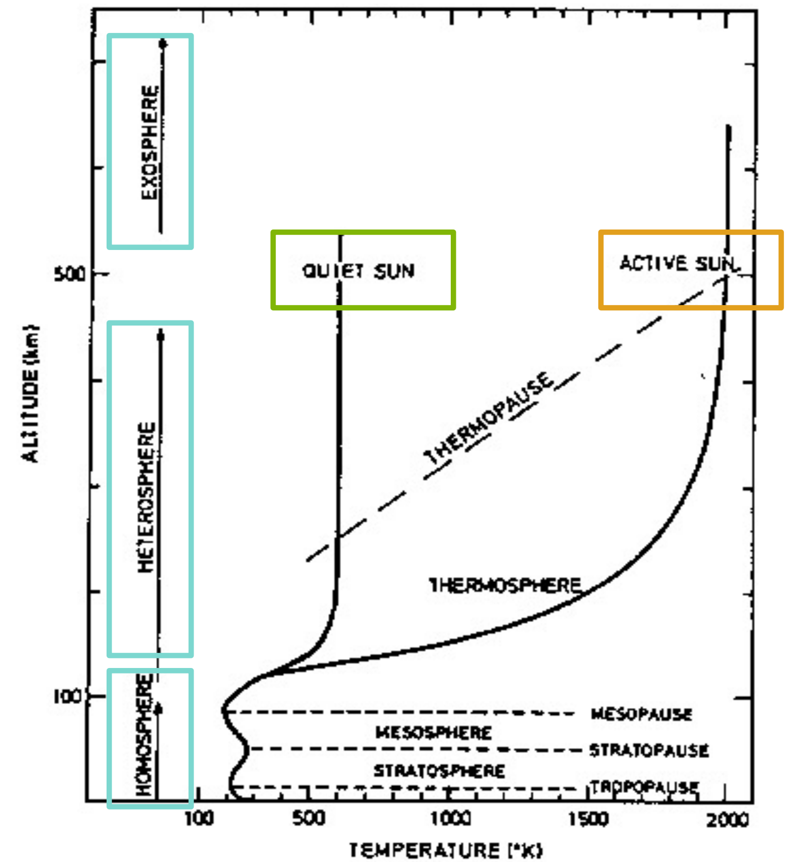



Fig 2. Vertical temperature distribution in the earth's atmosphere with emphasis on the thermosphere. (After P. M. Banks and G. Kockarts, "Aeronomy," Academic Press, New York, 1973, Part A, p. 3.)

# Neutral atmospheric layers

EXOSPHERE

- From the top of the thermosphere to the space
- L ~ 160 km (h > 800 km)
- H, He
- Light atmospheric constituents whose velocity exceeds the gravitational escape velocity can escape the atmosphere

# Atmospheric retention

The ability of a planet to retain an atmosphere reflects a competition between thermal velocity and escape velocity

$$E_{total} = E_k + E_p = 1/2mv^2 - \frac{GMm}{r} = 0 \longrightarrow v_{esc} = \sqrt{\frac{2GM}{R}}$$

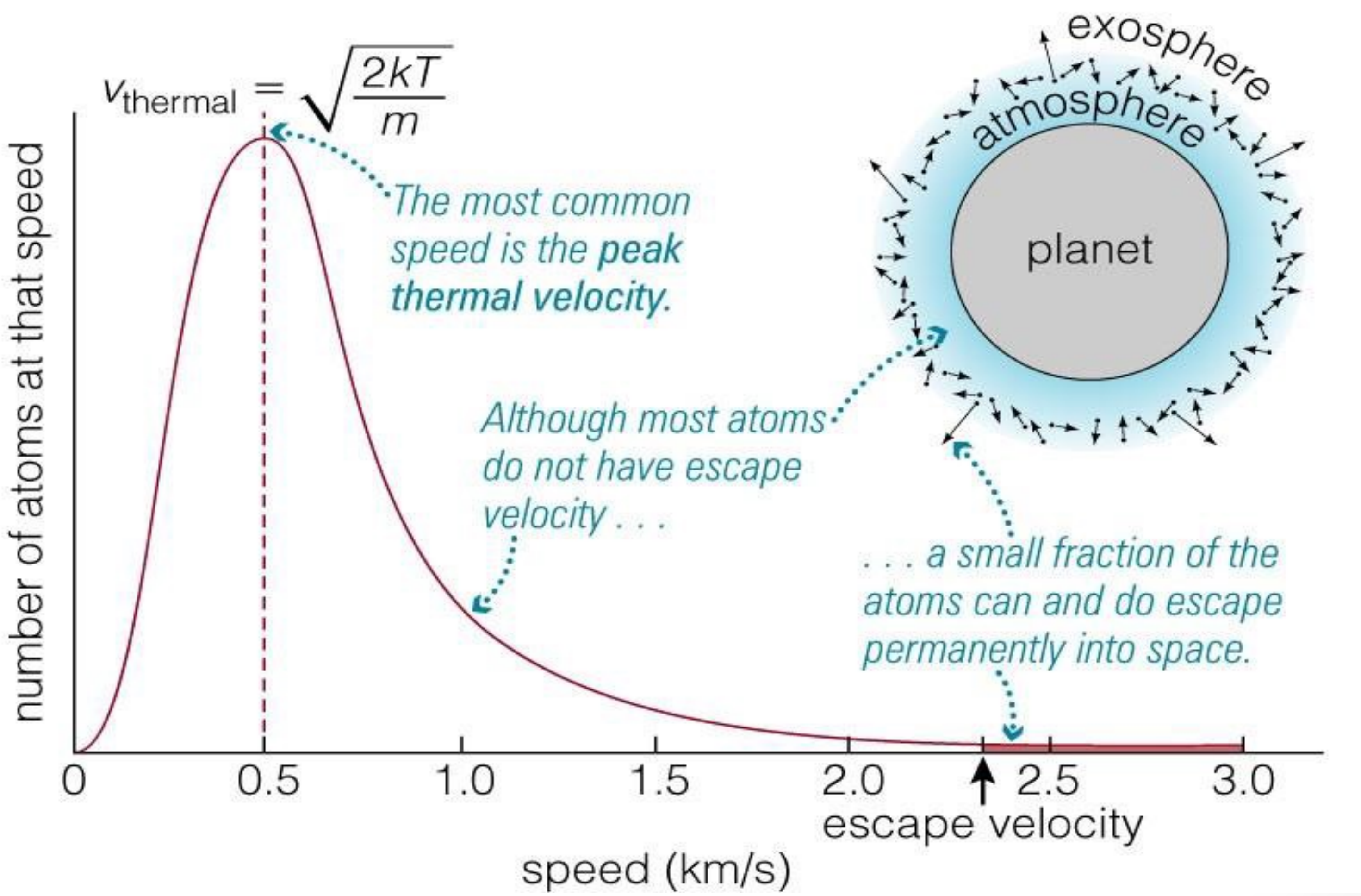
$$1/2mv_{therm}^2 = 3/2kT \longrightarrow v_{therm} = \sqrt{\frac{3kT}{m}}$$

$$\sqrt{\frac{3kT}{m}} = \sqrt{\frac{2GM}{R}} \Rightarrow T_{esc} = \frac{2GMm}{3kR}$$

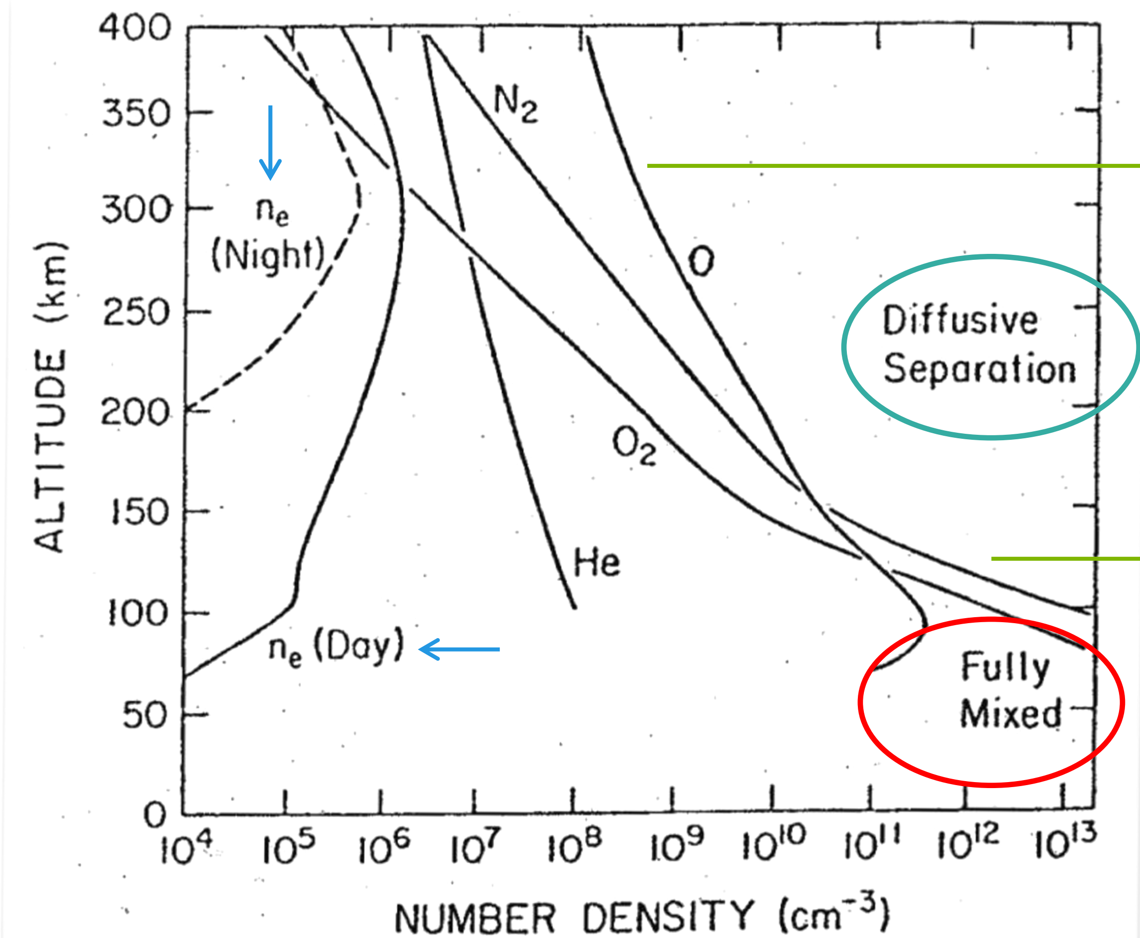
**Atmospheric retention condition**: the mean thermal velocity has to be several times lower than the escape velocity

$T_{atm} < T_{esc}$

# Atmospheric retention



# Neutral atmosphere composition



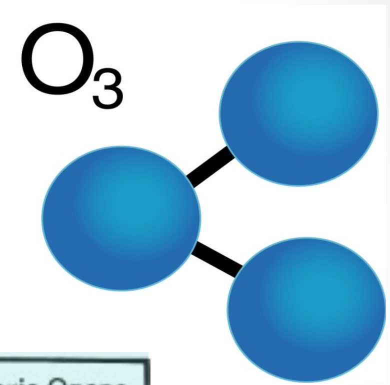

H, He dominate at highest altitude

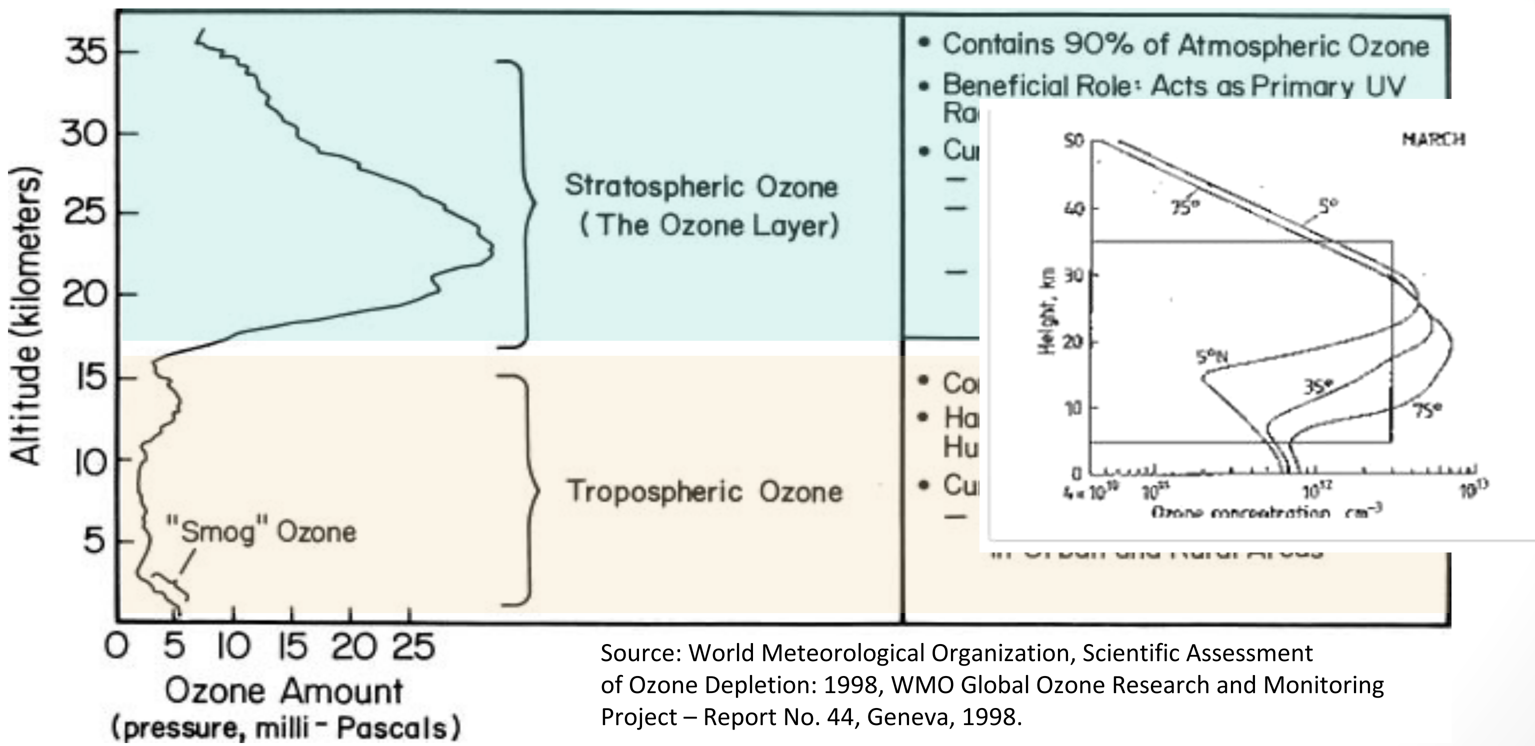
O, $O_2$ dominate at higher altitude where its low weight is important

$N_2$ dominates at low altitude

# Atmospheric Ozone

- Ozone is a gas made up of three oxygen atoms ($O_3$).
- $\rho\ \sim 0.001\%$ in volume
- Absorb UV radiation ($\lambda\ = 200 - 315$ nm), Ozone peak absorption at $\lambda \sim\ 250$ nm.




Source: World Meteorological Organization, Scientific Assessment of Ozone Depletion: 1998, WMO Global Ozone Research and Monitoring Project – Report No. 44, Geneva, 1998.

# Atmospheric Ozone

## The Chapman Cycle: *Oxygen - only Chemistry*

Four chemical reactions

- *Initiation* $O_2$ + light → 2O (120 – 210 nm)
- *Propagation* (cycling)

  $O + O_2 + M$ → $O_3 + M^*$ (generates heat)

  $O_3$ + light → $O_2 + O$ (220 – 320 nm)

- *Termination* $O_3 + O$ → $2O_2$

Qualitative agreement with observation:
presence of an ozone layer at the right height; predicts thermal inversion. But…

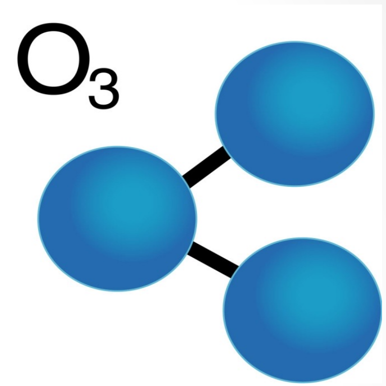
Predicts too much ozone

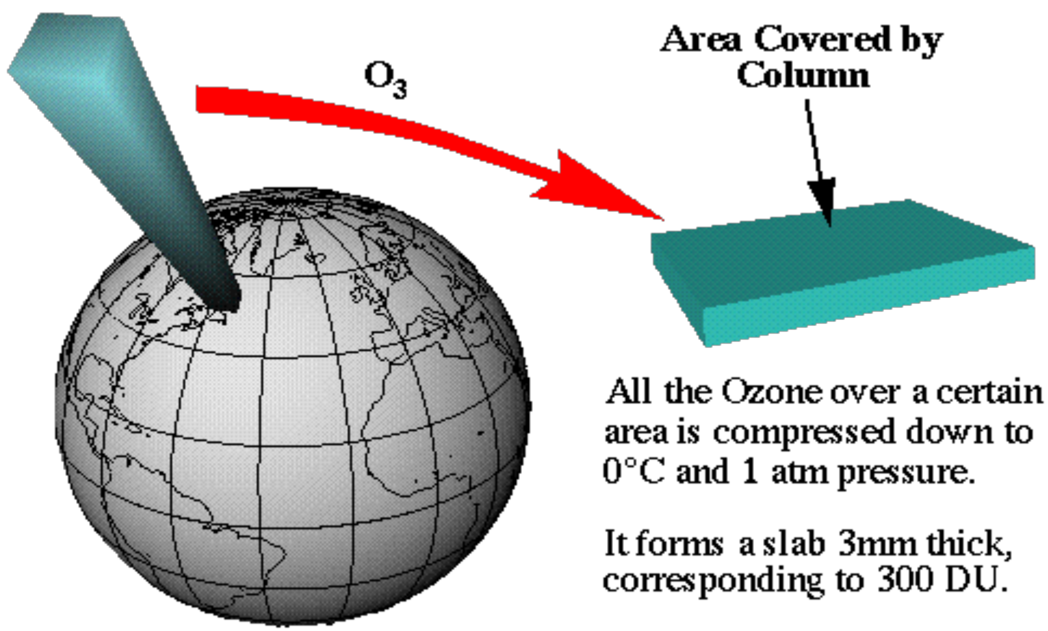
# Atmospheric Ozone

- **Ozone** levels are reported in Dobson Units (DU)

1DU = **0.01 mm thickness at STP**

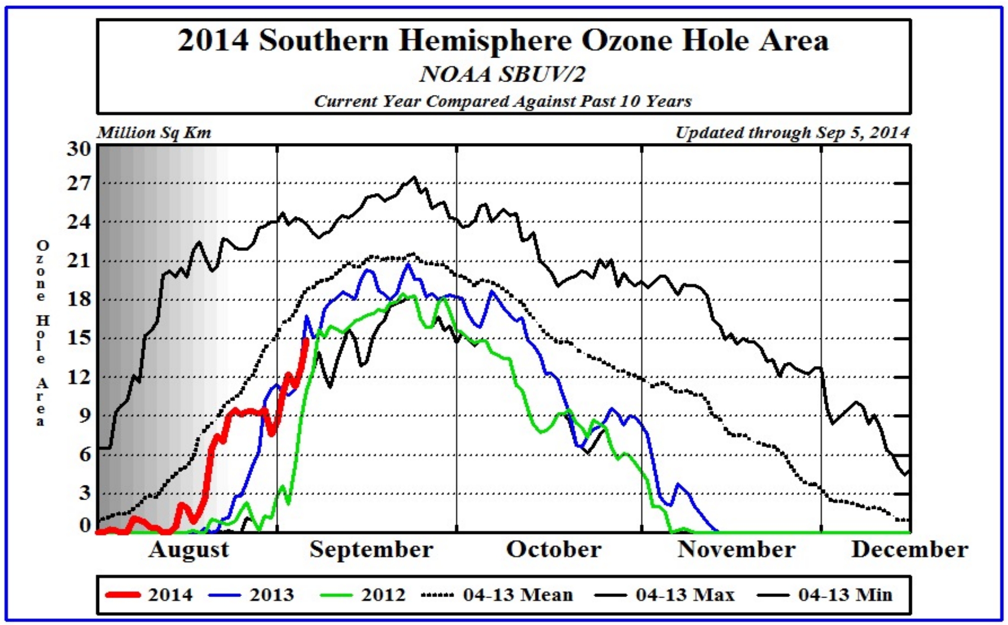
- 300 DU = standard mean Ozone concentration
- Geographic area with **less than 220 DU** = Ozone hole

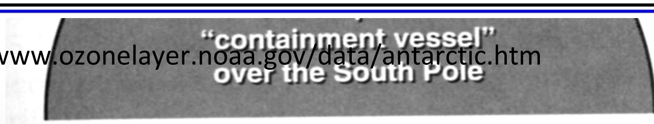


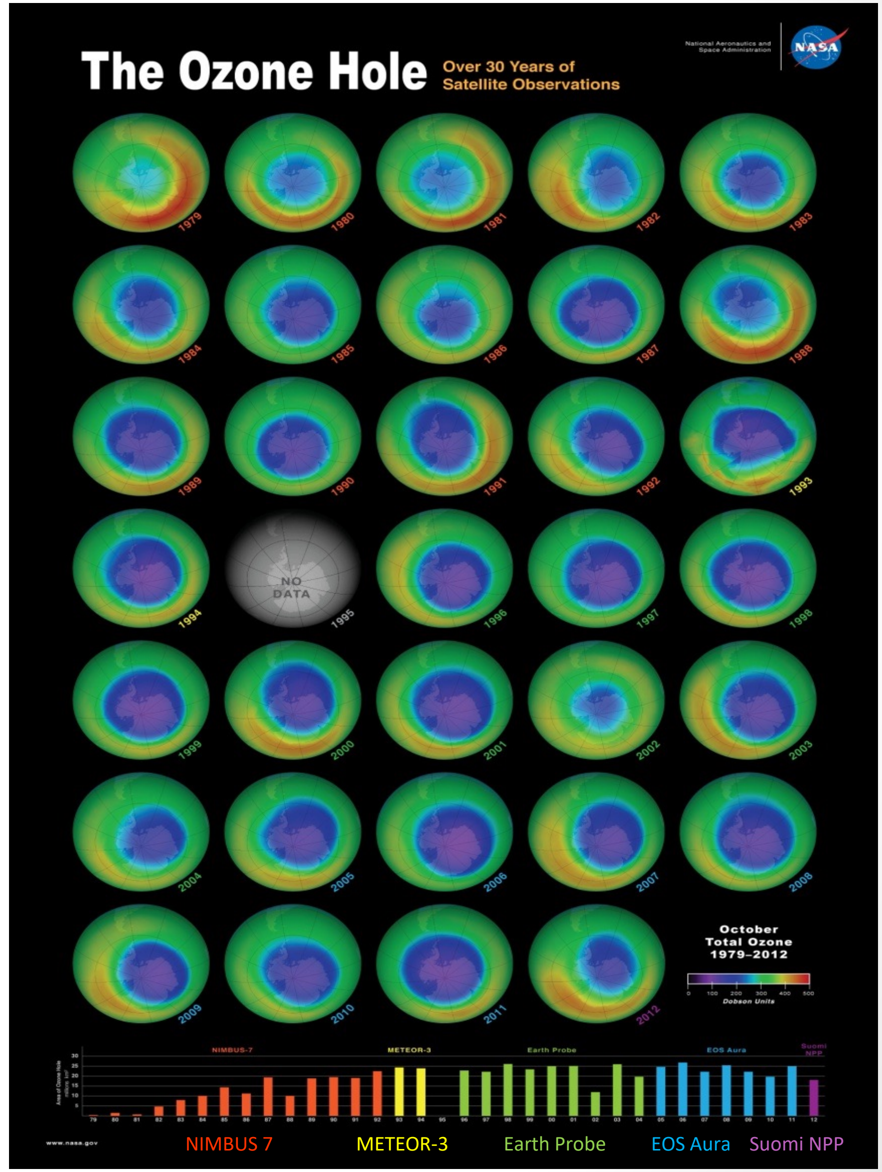
# Atmospheric Ozone depletion

- 1970’s abnormal depletion over poles
- Polar weather
- CFC’s

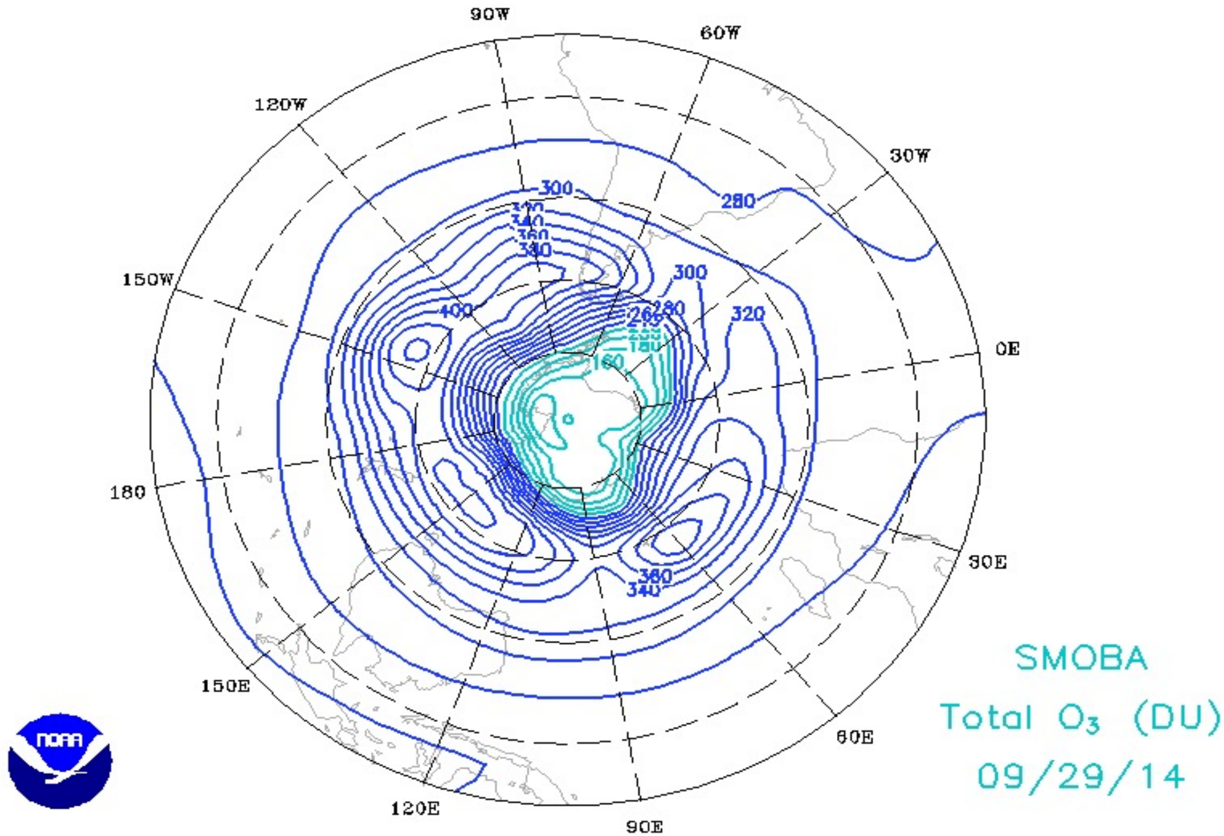



http://www.ozonelayer.noaa.gov/data/antarctic.htm

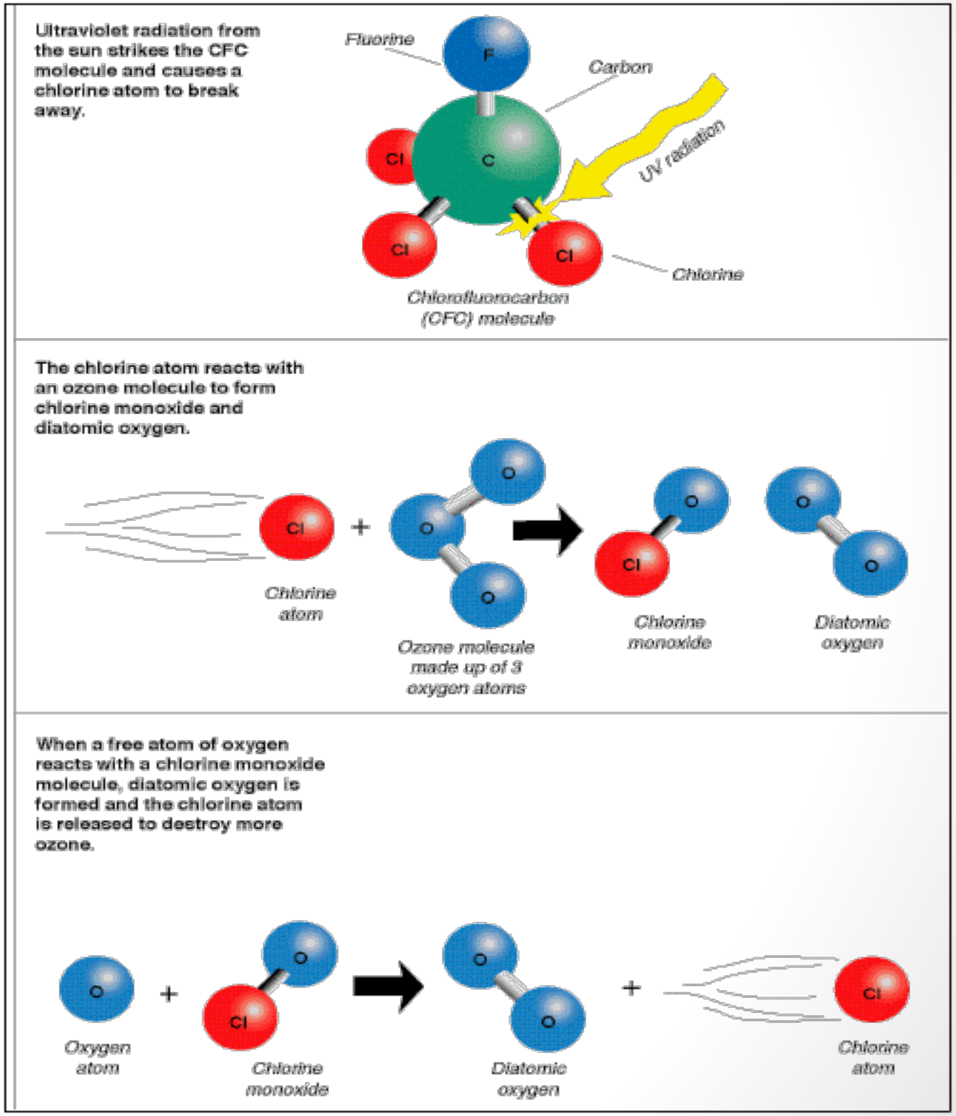


# Atmospheric Ozone depletion



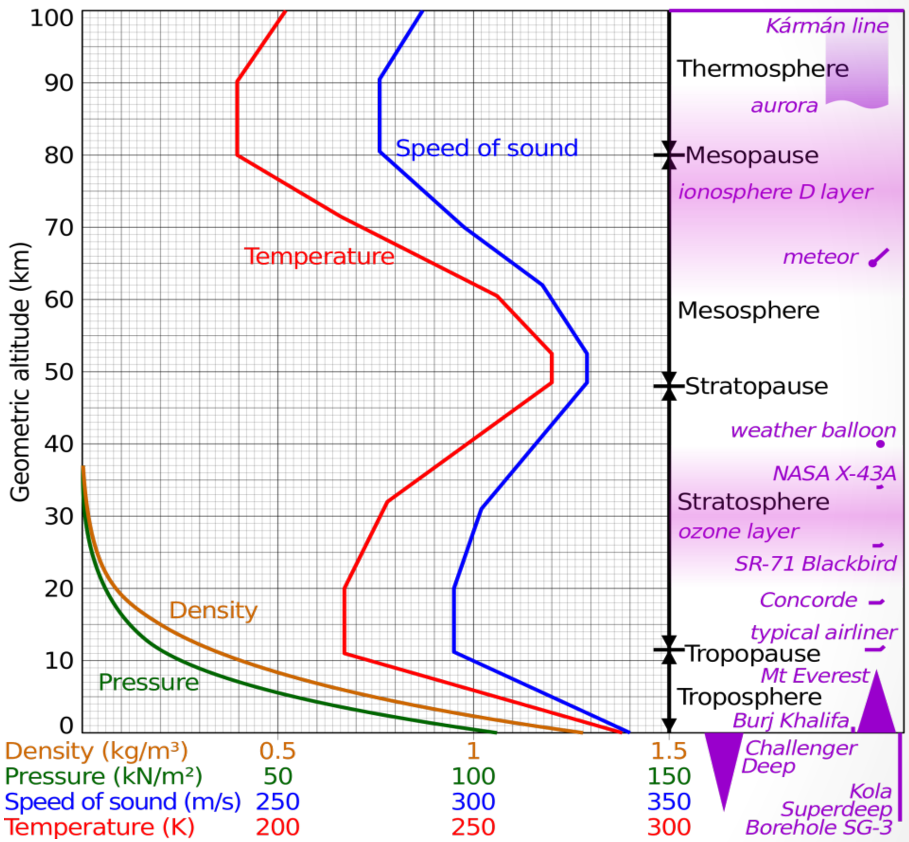
# CFCs interaction with $O_3$

- CFCs are ***chlorofluorocarbons***; they are small molecules that contain chlorine, fluorine and carbon atoms
- CFCs can reach the stratosphere where they are **photodissociated** by UV radiation (200-220 nm)
- They release **chlorine or bromine** that damage the protective ozone layer.
- One chlorine atom can destroy over 40,000 ozone molecules.
- **Greenhouse gases**



# Atmospheric measures: ρ, v, T

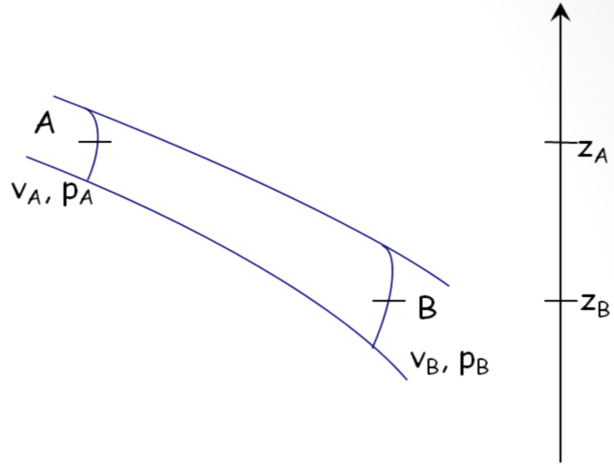
- Balloons (30 ÷ 35 km)
- Sounding rocket (40 ÷ 200 km)
  - Explosions
  - Release of tracer (Na)
  - Pitot tubes
  - Barometric Equation
- Satellite
  - Orbital Measures
  - Instruments

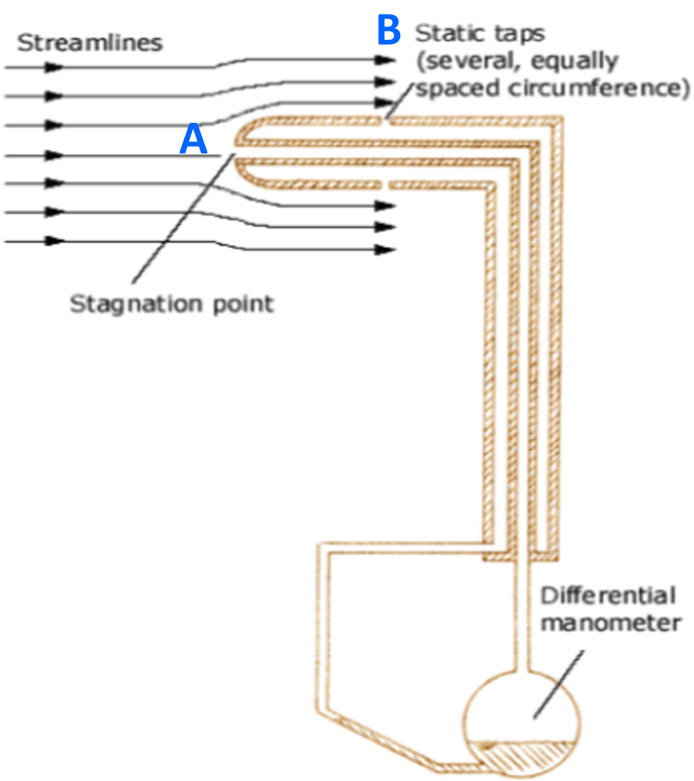


# Pitot tube

Eq. Bernoulli

$p_A + \rho g z_A + \rho v_A^2/2 = p_B + \rho g z_B + \rho v_B^2/2 = cost$




A:
stagnation pressure = static pressure + dynamic pressure

$$p_A = p + \rho v^2 / 2$$

$$\Delta p = p_A - p = \rho_{Hg}\, g\, \Delta h$$

$$= \rho v^2 / 2$$

$$\Downarrow$$

$$v, \rho$$

# Barometric equation

$F_g \quad = m\,g' = G\,Mm\,/\,R^2 = G\,Mm\,/(R_T+h)^2 =$

$= GM/R_T^2\; mR_T^2\,/\,(R_T+h)^2 = m\,gR_T^2/(R_T+h)^2 =$

$\Rightarrow g' = g\,R_T^2\,/\,(R_T+h)^2$

$E \quad = mg'h = m\,g\,R_T^2/(R_T+h)^2\,h = mgh'$

$\Rightarrow h' = h\,R_T^2\,/\,(R_T+h)^2$ = altezza geopotenziale

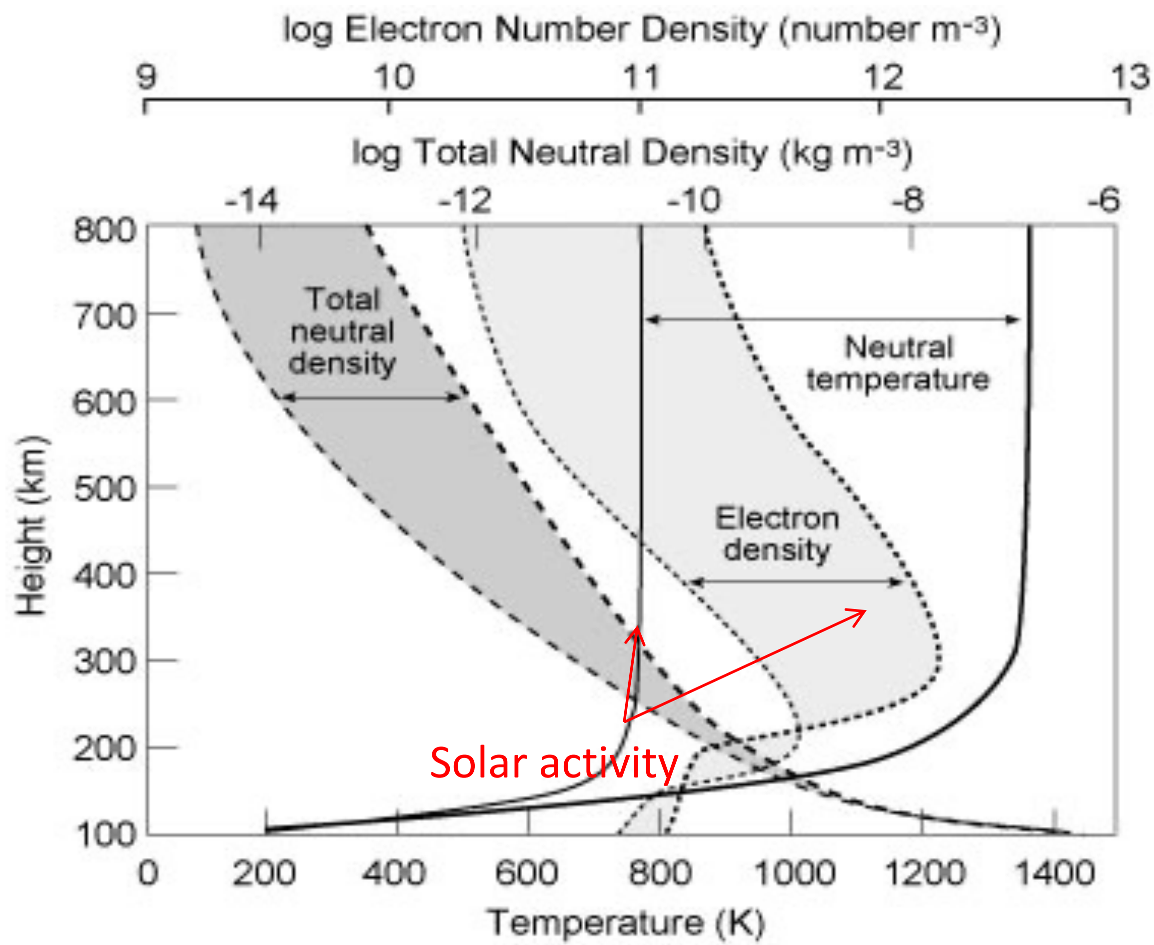
$n \sim e^{-E/kT} = e^{-mgh'/kT}$ (statistica di Boltzmann)

$n_1/n_2 = e^{-mg(h1'-h2')/kT}$

$\Rightarrow \ln(n_1/n_2) = -mg(h_1'-h_2')/kT = -d/D$ eq. Barometrica

$D = kT/mg$ = altezza di scala, $d = h_1'-h_2'$

# Atmospheric density and solar activity

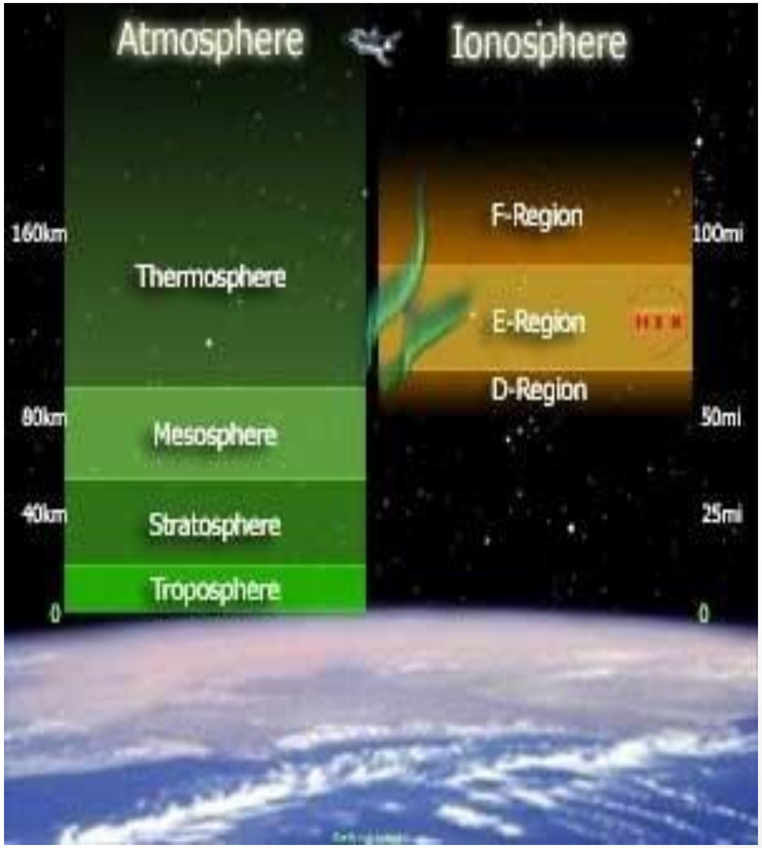



Courtesy of Judith Lean

# Ionosphere

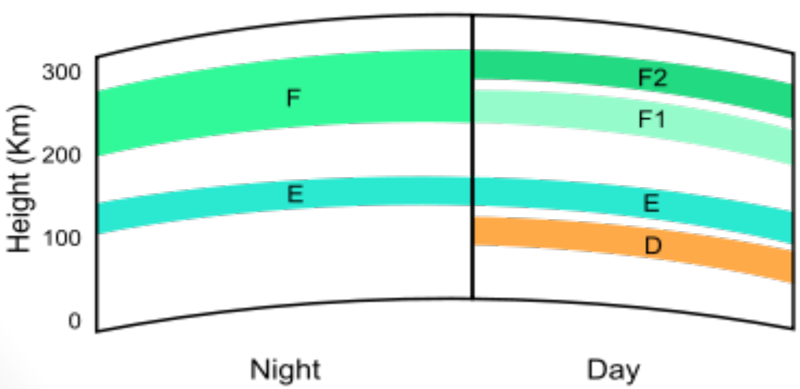
The ionosphere is defined as the layer of the Earth's atmosphere that is ionized by solar and cosmic radiation

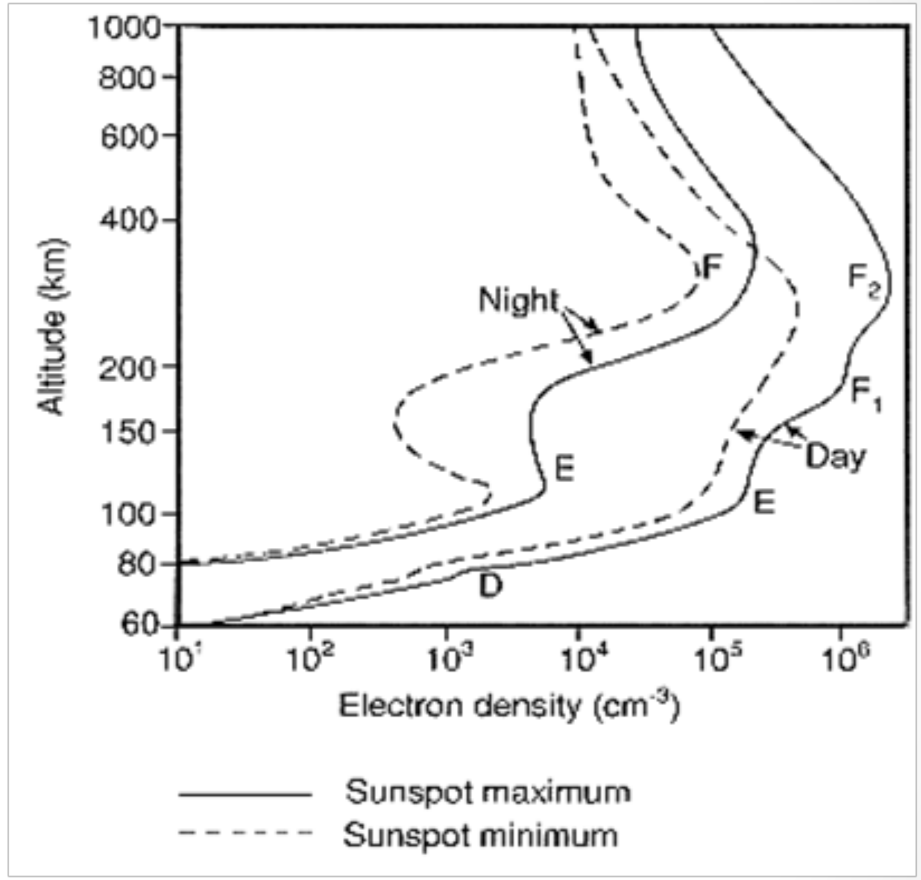
- This region of partially ionized gas extends upwards to high altitudes 75-1000 km where it merges with the magnetosphere
- Discovered in the early 1900s in connection with long distance radio transmissions (Marconi)
- Scientists postulated, and later proved, that long distance radio communication was possible due to reflection off of an ionized region in the atmosphere



# Ionosphere

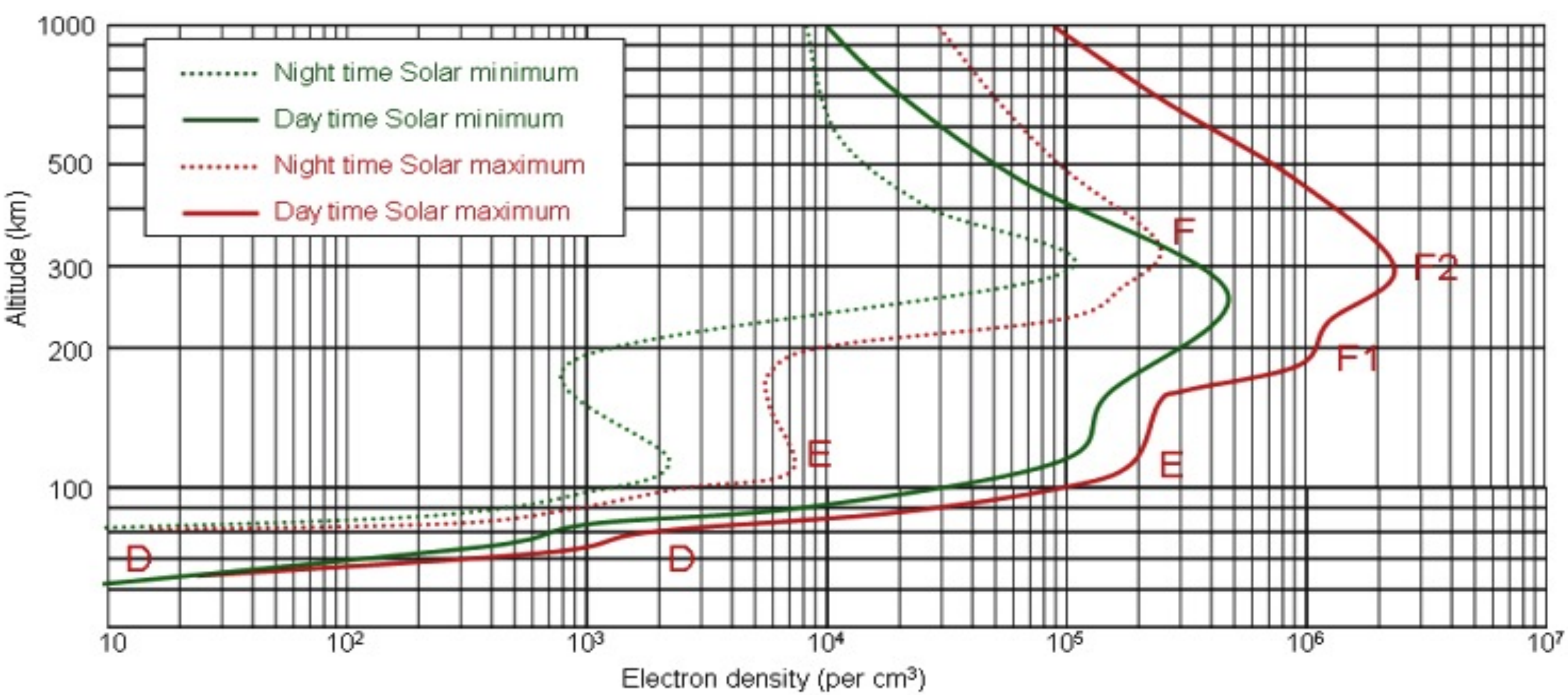
- Day – night variation
- Solar activity influence
- Ion/neutral ratio ($n/n_n$) (Weak ionization)
  - $10^{-8}$ at 100 km
  - $10^{-3}$ at 300 km
  - $10^{-2}$ at 1000 km



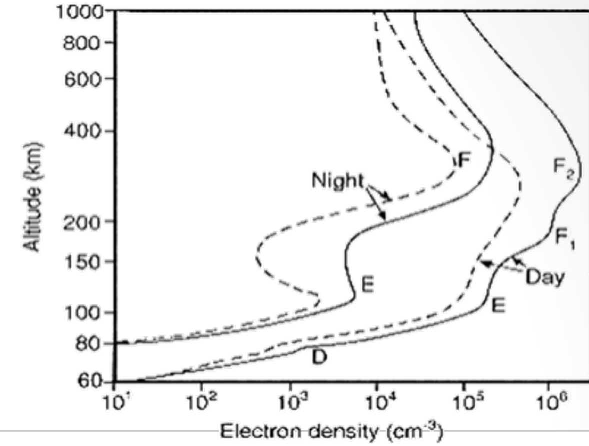

- D region (≈60–90 km, peaks around 90 km);
- E region (≈90–140 km, peaks around 110 km);
- $F_1$ region (≈140–200 km, peaks around 200 km);
- $F_2$ region (≈200–500 km, peaks around 300 km);
- Topside ionosphere (above the $F_2$ region).

# Ionosphere: solar activity variations



# Ionospheric Composition

- Composition of the dayside ionosphere under solar minimum conditions.
  - At low altitudes the major ions are **$O_2^+$** and **$NO^+$**
  - Near the $F_2$ peak it changes to **$O^+$**
  - The topside ionosphere becomes **$H^+$** dominant.
- Quasi-neutral (net charge ~ zero in each volume element with enough particles).
- Formed mainly by ionization of $N_2$, $O_2$, and O.
- The primary ionization mechanism is photoionization by EUV and X-ray radiation.
  - In some areas ionization by particle precipitation is also important.



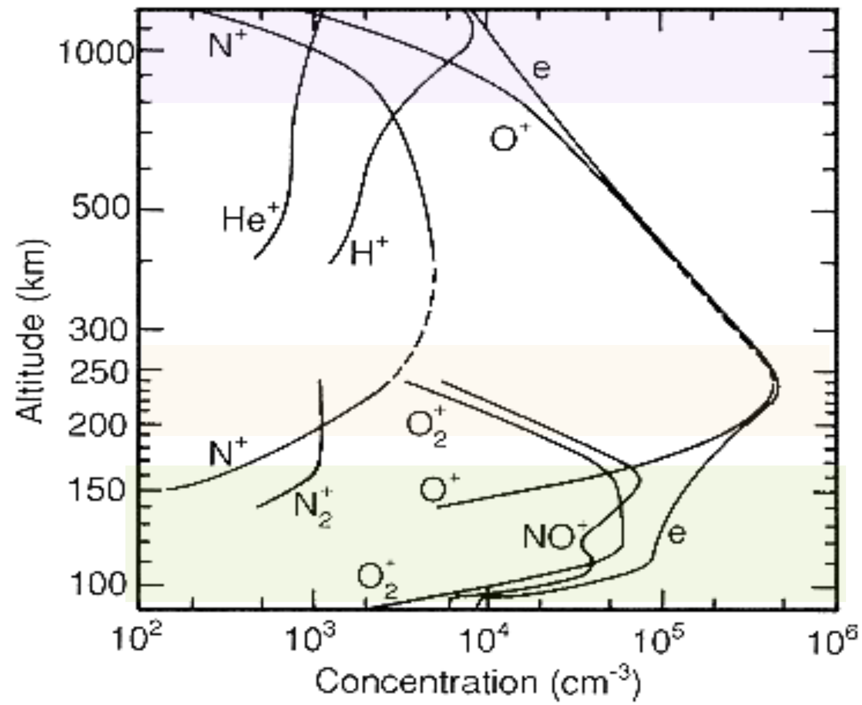




**Figure 10.2** Typical composition of the dayside ionosphere at solar minimum. (From *Johnson*.[1])

# Ionosphere: formation

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
  - $A + \gamma \rightarrow A^+ + e^-$

D (NO): Ly-$\alpha$ (121.6 nm) + cosmic rays
E ($O_2$, NO, O): Soft X (10-100 nm) + EUV (<91.2nm)
F (O): EUV (10.0-91.2 nm)

- Recombination: $n_{ione} \sim n_e \Rightarrow$ prob. $\sim n_e^2$
  - $A^+ + e^- \rightarrow A' + \gamma$
  - $BC^+ + e^- \rightarrow B' + C'$ — E
  - $D + e^- \rightarrow D^-$ — D
  - $O^+ + O_2 \rightarrow O + O_2^+$ ; $O_2^+ + e^- \rightarrow O' + O'$ — F

# Ionospheric Layers

- The D Region
  - The most complex and least understood layer in the ionosphere.
  - The primary source of ionization in the D region is ionization by solar X-rays and Lyman-ionization of the NO molecule.
  - Precipitating magnetospheric electrons may also be important.
  - The primary positive ions are $O_2^+$ and $NO^+$
  - The most common negative ion is $NO_3^-$
- The E Region
  - Essentially a Chapman layer formed by EUV ionization.
  - The main ions are $O_2^+$ and $NO^+$
  - Although nitrogen ($N_2$) molecules are the most common in the atmosphere $N_2^+$ is not common because it is unstable to charge exchange. For example

$$N_2^+ + O_2 \rightarrow O_2^+ + N_2$$

$$N_2^+ + O \rightarrow NO^+ + N$$

$$N_2^+ + O \rightarrow O^+ + N_2$$

  - Oxygen ions are removed by the following reactions:

$$O^+ + N_2 \rightarrow NO^+ + N$$

$$O^+ + O_2 \rightarrow O_2^+ + O$$

# Ionospheric Layers

- The $F_1$ Region
  - Essentially a Chapman layer.
  - The ionizing radiation is EUV at <91nm.
  - It is basically absorbed in this region and does not penetrate into the E region.
  - The principal initial ion is $O^{+}$.
  - $O^{+}$ recombines in a two step process.
    - First atom ion interchange takes place

$$O^{+} + N_2 \rightarrow NO^{+} + N$$

$$O^{+} + O_2 \rightarrow O_2^{+} + O$$

    - This is followed by dissociative recombination of $O_2^{+}$ and $NO^{+}$

$$O_2^{+} + e \rightarrow O + O$$

$$NO^{+} + e \rightarrow N + O$$

# Ionospheric Layers

- The $F_2$ Region
  - The major ion is $O^+$
  - This region is not a Chapman
  - This region is formed by an interplay between ion sources, sinks and ambipolar diffusion.
  - The dominant ionization source is photoionization of atomic oxygen

$$O + h\nu \rightarrow O^+ + e$$

  - The oxygen ions are lost by a two step process
    - First atom-ion interchange

$$O^+ + O_2 \rightarrow O_2^+ + O$$
$$O^+ + N_2 \rightarrow NO^+ + N$$

    - Dissociative recombination

$$O_2^+ + e \rightarrow O + O$$
$$NO^+ + e \rightarrow N + O$$

  - The peak forms because the loss rate falls off more rapidly than the production rate.
  - The density falls off at higher altitudes because of diffusion- no longer in local photochemical equilibrium.

# Electron density

- Positive ions density (h>1000 km):

$$\ln(n_{i,1}/n_{i,2}) = - m_i g(h_1'-h_2') / k(T_i+T_e)$$
$$= - d/D$$

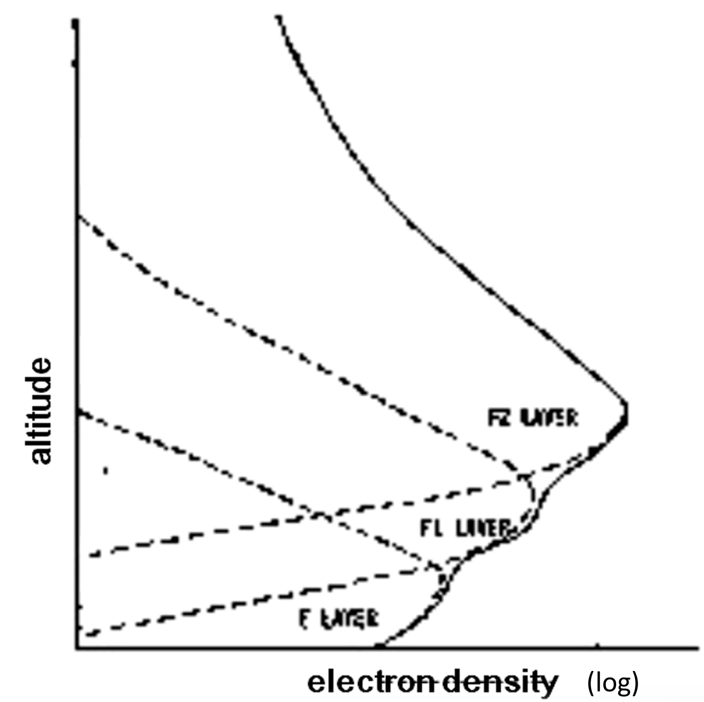
$D=k(T_i+T_e)/m_i g$ geopotential height

- At these altitudes $n_{ione} \sim n_e$ so the same eq is valid for the electron density

$$\text{Log } n_e = -\text{Log}(e)\ d/D$$
$$d = -D \text{ Log } n_e/\text{Log}(e)$$
$$d = -2.3\ D \text{ Log } n_e$$

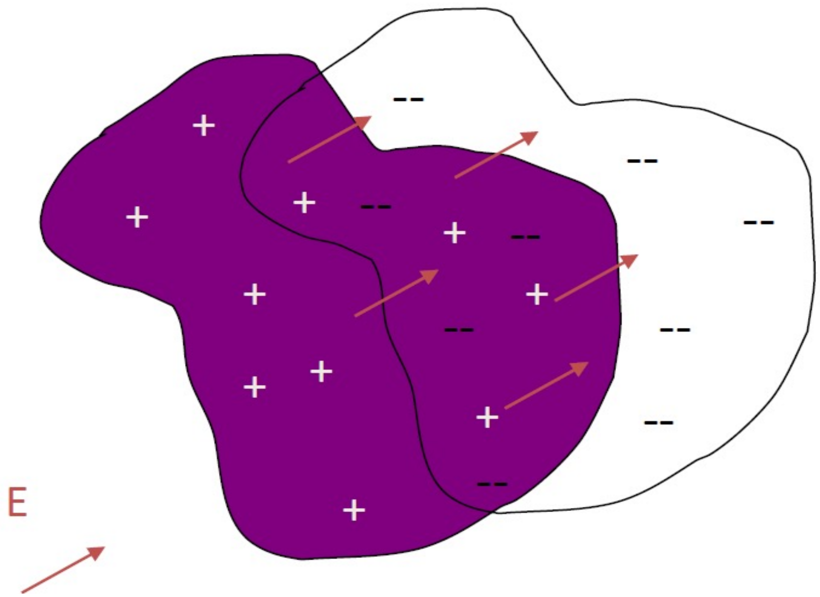
↓

$O^+ / He^+$



# Ionospheric plasma

A plasma is a gaseous mixture of electrons, ions, and neutral particles. The ionosphere is a weakly ionized plasma.

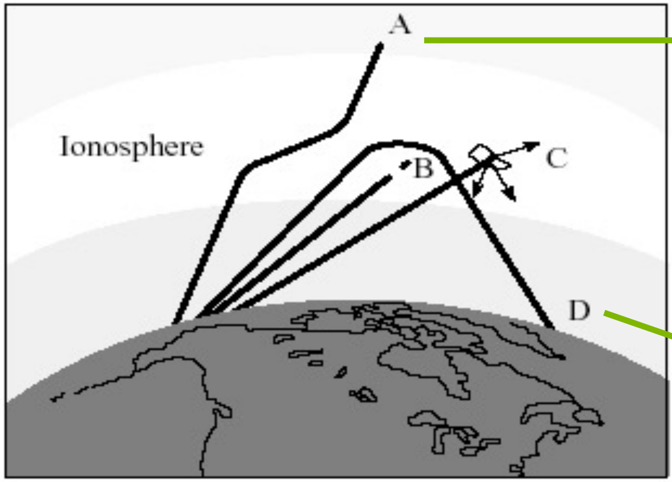



If, by some mechanism, electrons are displaced from ions in a plasma, the resulting separation of charge sets up an electric field which attempts to restore equilibrium. Due to their momentum, the electrons will overshoot the equilibrium point, and accelerate back. **This sets up an oscillation.**

The frequency of this oscillation is called the ***plasma frequency:*** $f_p = 2 \times f = (4 \times N_e e^2/m_e)^{1/2}$ which depends upon the properties of the particular plasma under study

# Radio Waves in an Ionospheric Plasma

A radio wave consists of oscillating electric and magnetic fields. When a low-frequency radio wave (i.e.,$f < f_{plasma}$) impinges upon a plasma, the local charged particles have sufficient time to rearrange themselves so as to “cancel out” the oscillating electric field and thereby “screen” the rest of the plasma from the oscillating E-field.




For a high frequency wave (i.e., $f > f_{plasma}$), the particles do not have time adjust themselves to produce this screening effect, and the wave passes through (A).

Wave is absorbed within the ionosphere (B)

Wave is scattered in random directions by plasma irregularities (C)

This low frequency radio wave cannot penetrate the plasma, and is reflected (D).

The critical frequency of the ionosphere ($f_oF2$) represents the minimum radio frequency capable of passing completely through the ionosphere.

# Radio Waves vs Ionosphere

Energy absorption / wave refraction

$u = c/(1 - e^2 n_e / \pi m_e \nu^2)^{1/2}$ phase vel for a wave in a ionized medium

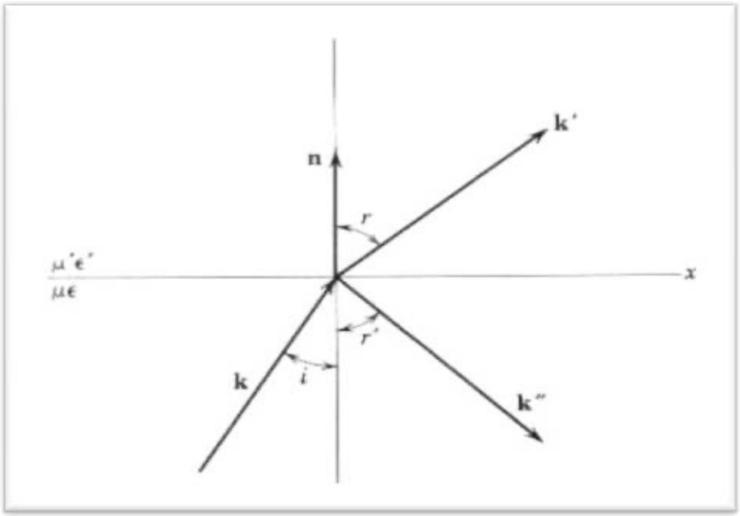
$n = c/u = (1 - 8.06\times10^{-5} n_e / \nu^2)^{1/2}$ refractive index ionized medium

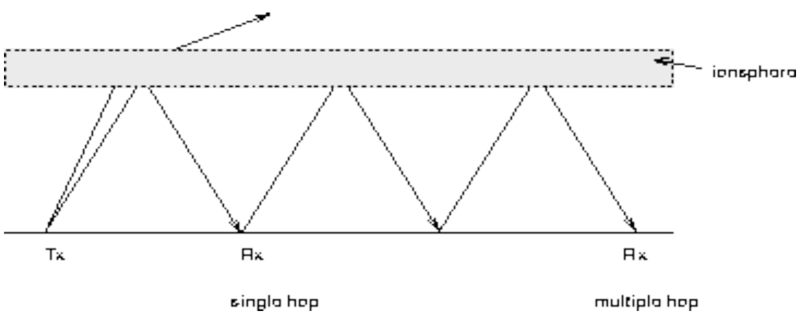
$n_e^c = 1.24\times10^4 \nu^2 \cdot \cos^2 i$ critical density, n = 0

$\nu^c = 8.98\times10^{-3} \sqrt{n_e} / \cos i$ critical frequency

$n_e$ in cm-3
$\nu$ in MHz

# Snell's law




$n = ( \mu \varepsilon )^{½}$

$\sin i / \sin r = n' / n$

$\mu = cost$

$\varepsilon = E_{vacuum} / E_{iono}$

ionosphere: thin electron plasma, trapped in a strong magnetic field, static and uniform

# Ionogram

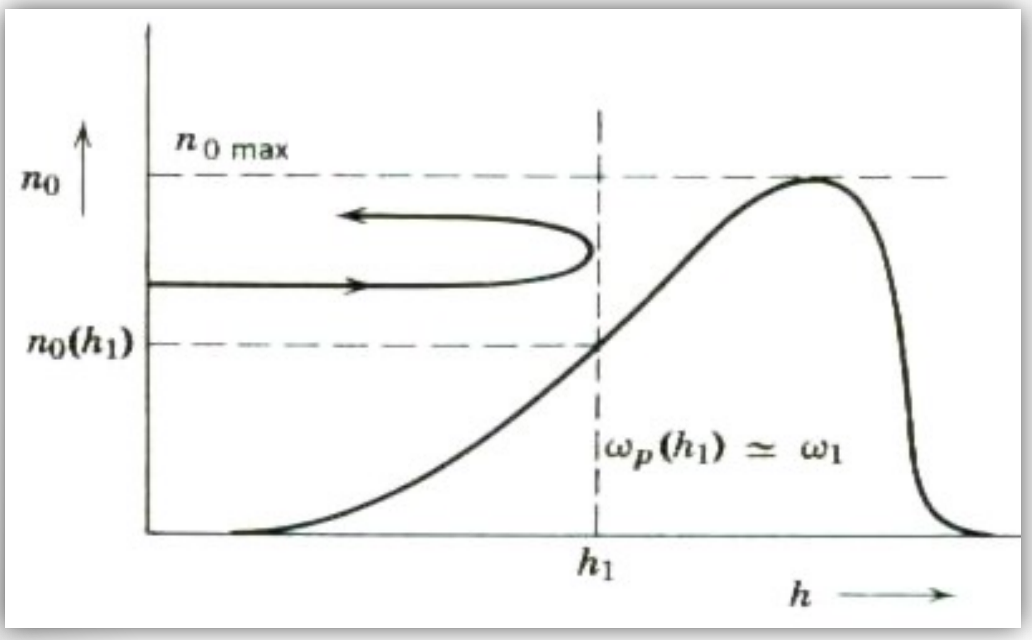
http://ecjones.org/physics.html

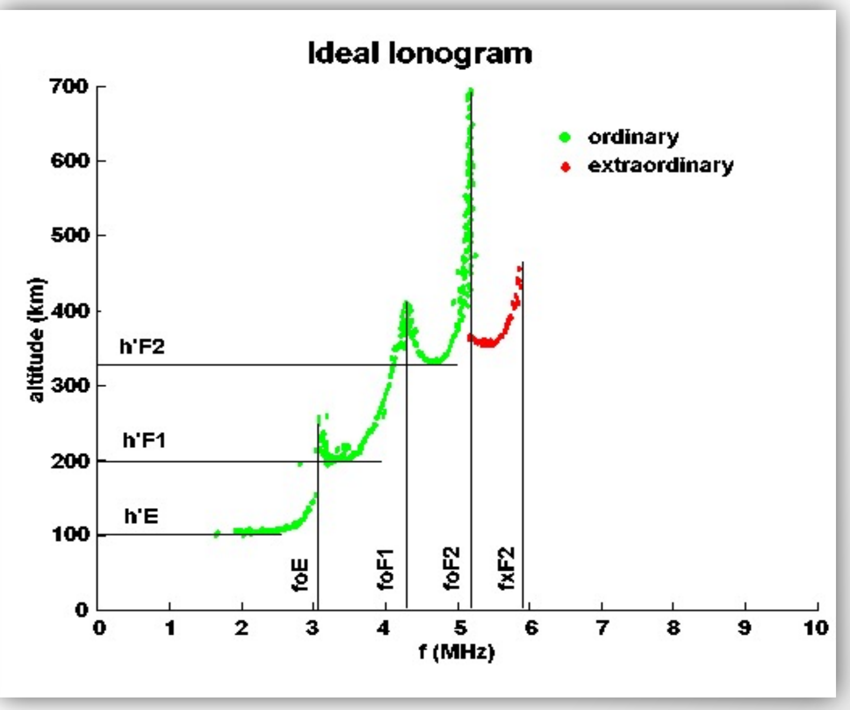
$\varepsilon_{\pm} = 1 - \omega_p^2 / \omega(\omega \pm \omega_B)$ (+/- circular pol. dx/sx, $\mathbf{E}=(\varepsilon_1 \pm i\varepsilon_2)E$)

$\omega_B = eB_0 / mc \sim 6\times10^6\ s^{-1}$

$\omega_p^2 = 4\pi NZ e^2 / m \sim 6\times10^6 \div 6\times10^7\ s^{-1}$

$n_0$



# Onde Radio VS Ionosfera 2/2

| Description | Frequency | Wavelength |
|---|---|---|
| High frequency | 3 - 30MHz | 100 - 10m |
| VHF | 50 - 100MHz | 6 - 3m |
| UHF | 400 -1000MHz | 75 - 30cm |
| Microwaves | $3 \times 10^9$ - $10^{11}$Hz | 10cm - 3mm |
| Millimetre waves | $10^{11} - 10^{12}$Hz | 3mm - 0.3mm |
| Infrared | $10^{12} - 6 \times 10^{14}$Hz | 0.3mm - 0.5$\mu$m |
| Light | $6 \times 10^{14} - 8 \times 10^{14}$Hz | 0.5 $\mu$m - 0.4$\mu$m |
| Ultra-violet | $8 \times 10^{14} - 10^{17}$Hz | 0.4$\mu$m - $10^{-9}$m |
| X-rays | $10^{17} - 10^{19}$Hz | $10^{-9}$m - $10^{-13}$m |
| Gamma rays | $> 10^{19}$Hz | $< 10^{-13}$m |

valutare $n_e^c$

valutare $\nu^c$

| Layer / $n_e$ ($cm^{-3}$) | Night | Day |
|---|---|---|
| D | 1.E+02 | 1.E+03 |
| E | 1.E+03 | 1.E+05 |
| F1 | 1.E+04 | 3.E+05 |
| F2 | 2.E+05 | 1.E+06 |

# Ionospheric disturbancies

- Maree e Venti Atmosferici
  - Strato D, E
- SID (Sudden Ionospheric Disturbances)
  - Strato D (onde corte)
- Tempeste Ionosferiche
  - Strato D (alta frequenza)
- Tempesta Aurorale