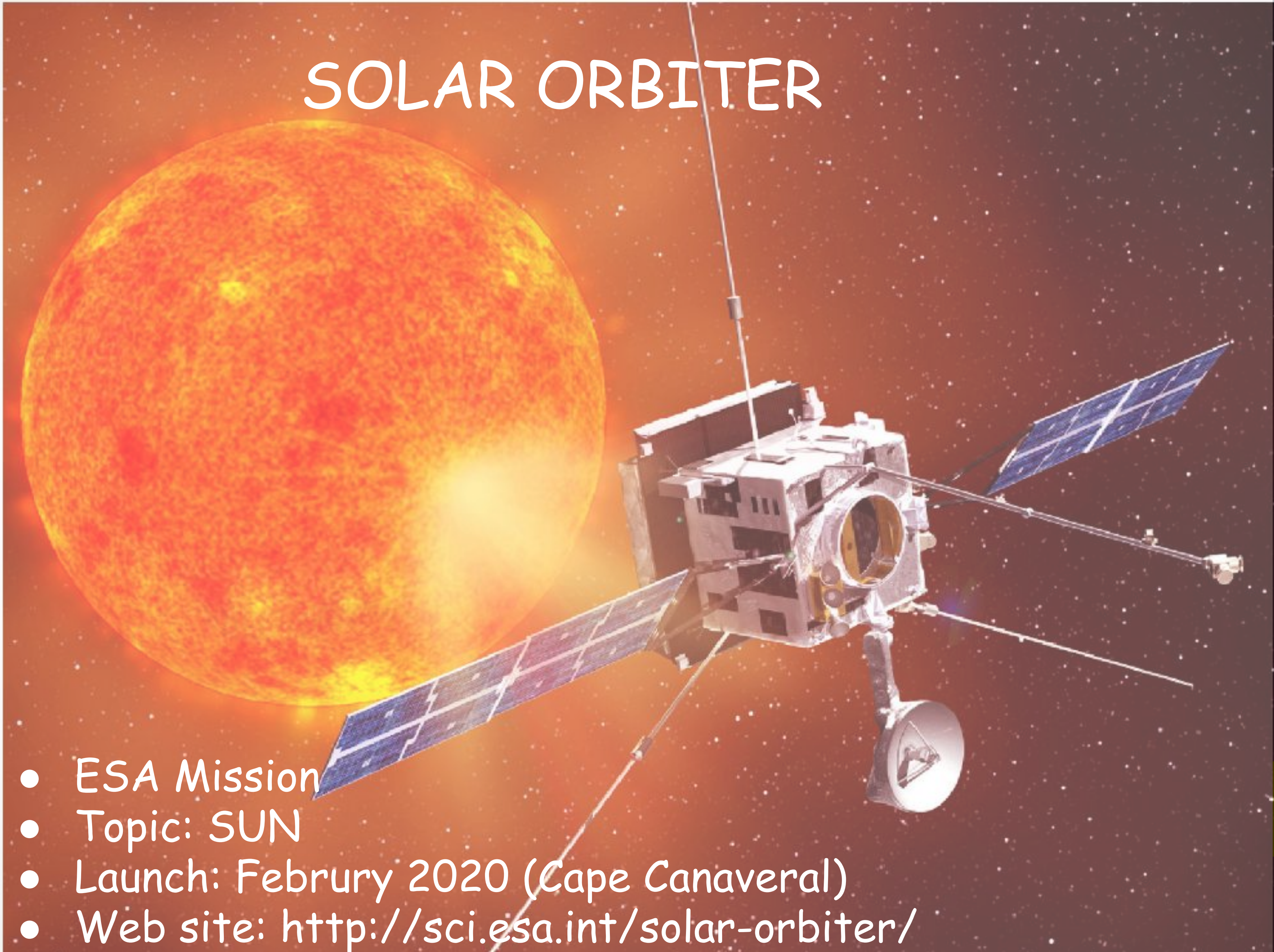
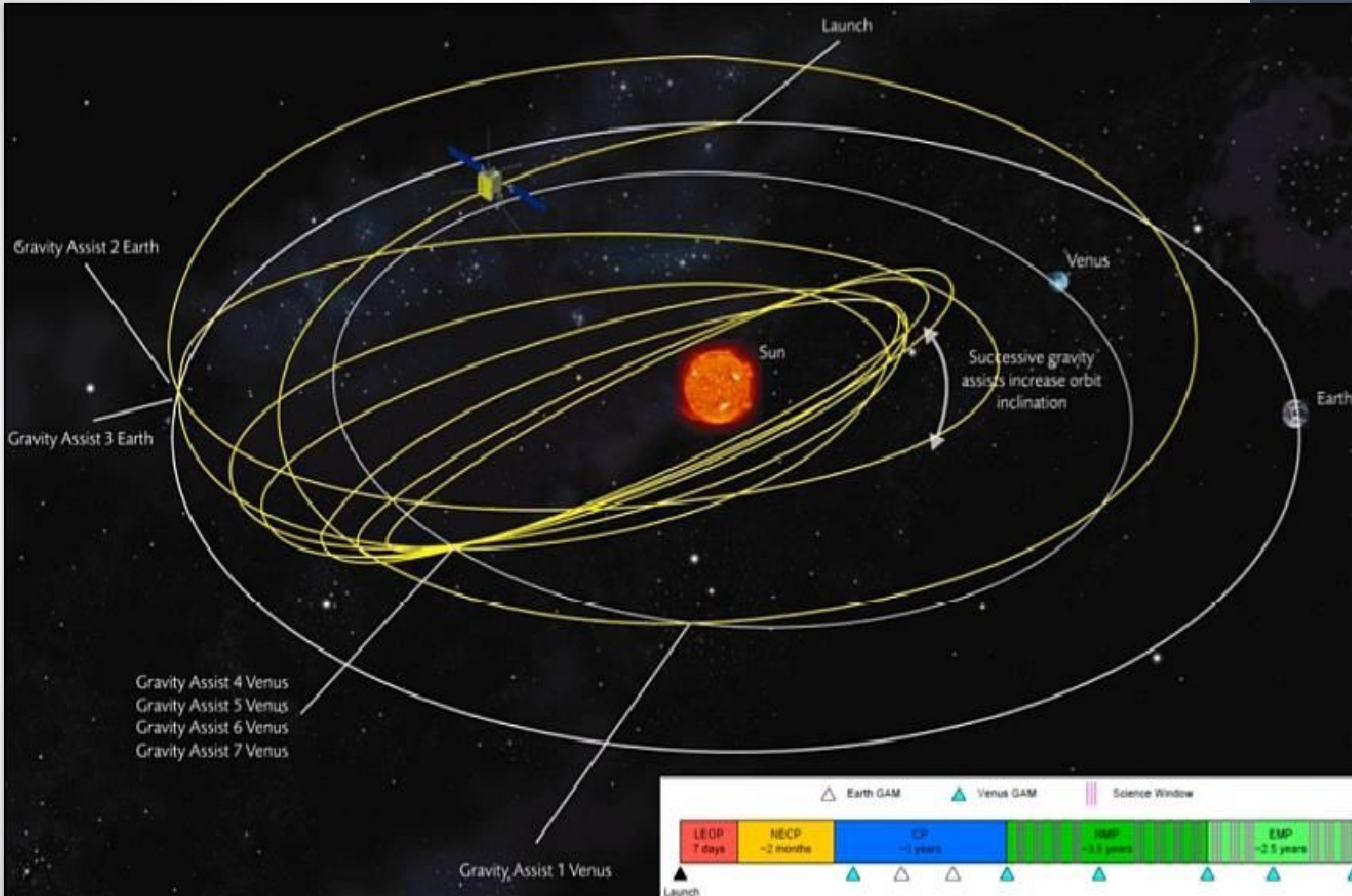
Earth’s Atmosphere

Giovanna Jerse (INAF, OATs)

SOLAR ORBITER



- ESA Mission
- Topic: SUN
- Launch: Februry 2020 (Cape Canaveral)
- Web site: http://sci.esa.int/solar-orbiter/


Launch
Gravity Assist 2 Earth
Venus
Sun
Successive gravity assists increase orbit inclination
Earth
Gravity Assist 3 Earth
Gravity Assist 4 Venus
Gravity Assist 5 Venus
Gravity Assist 6 Venus
Gravity Assist 7 Venus
Gravity Assist 1 Venus
Earth GAM
Venus GAM
Science Window
LEOP
7 days
NECP
~2 months
NMP
EMP
~2.5 years
Launch

SOLAR ORBITER

Payload

In-Situ Instruments			
EPD	Energetic Particle Detector	J. Rodríguez-Pacheco	Composition, timing and distribution functions of energetic particles
MAG	Magnetometer	T. Horbury	High-precision measurements of the heliospheric magnetic field
RPW	Radio & Plasma Waves	M. Maksimovic	Electromagnetic and electrostatic waves, magnetic and electric fields at high time resolution
SWA	Solar Wind Analyser	C. Owen	Sampling protons, electrons and heavy ions in the solar wind
Remote-Sensing Instruments			
EUI	Extreme Ultraviolet Imager	P. Rochus	High-resolution and full-disk EUV imaging of the on-disk corona
METIS	Multi-Element Telescope for Imaging and Spectroscopy	E. Antonucci	Imaging and spectroscopy of the off-disk corona
PHI	Polarimetric & Helioseismic Imager	S. Solanki	High-resolution vector magnetic field, line-of-sight velocity in photosphere, visible imaging
SoloHI	Heliospheric Imager	R. Howard	Wide-field visible imaging of the solar off-disk corona
SPICE	Spectral Imaging of the Coronal Environment	European-led facility instrument	EUV spectroscopy of the solar disk and near-Sun corona
STIX	Spectrometer/Telescope for Imaging X-rays	S. Krucker	Imaging spectroscopy of solar X-ray emission

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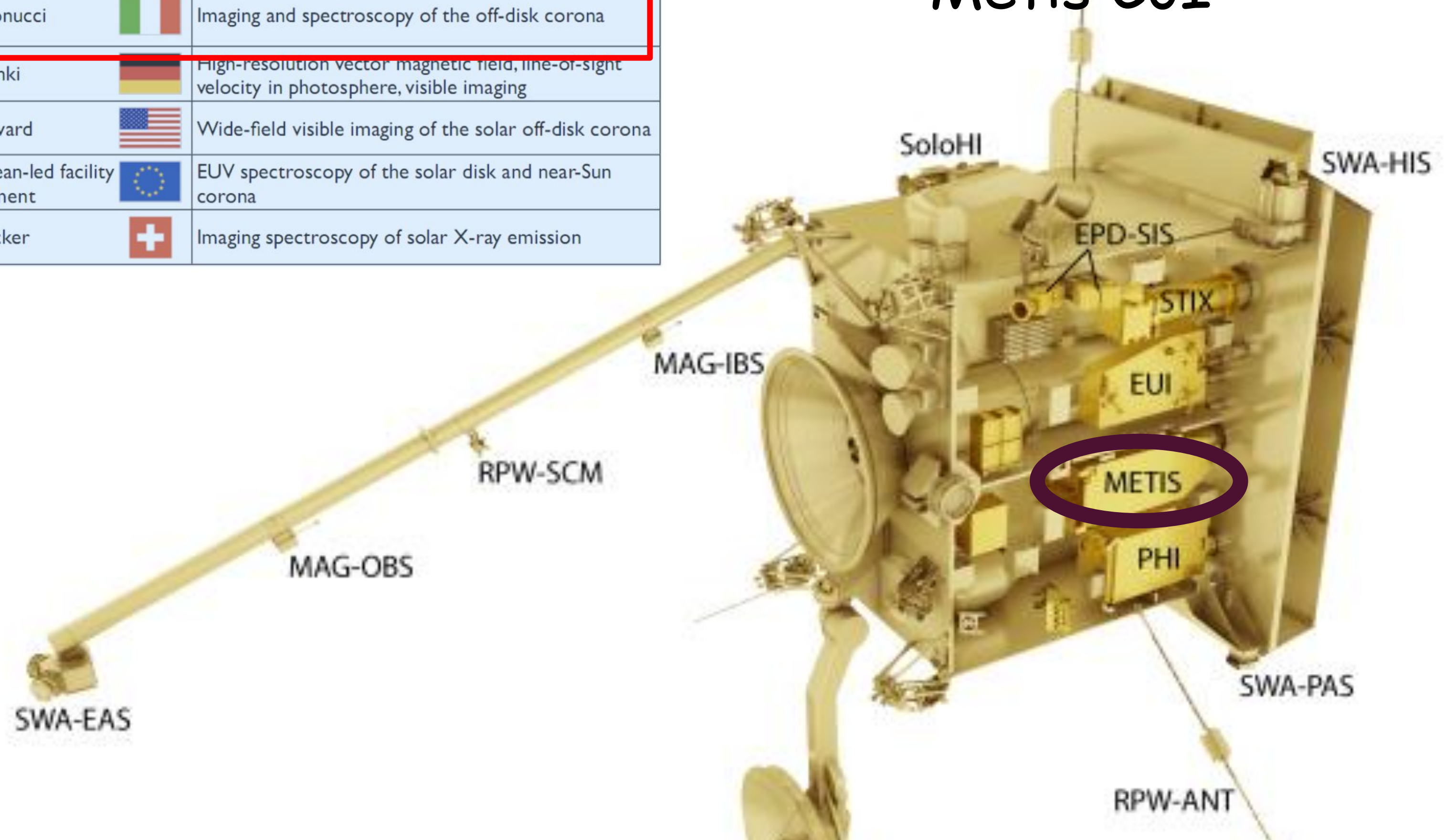


Metis Science Objectives

- Origin and Acceleration of the Solar Wind
- Sources of the Solar Energetic Particles
- Origin and Early Propagation of Coronal Mass Ejections
- Evolution of the Global Magnetic Field shaping of the Solar Corona

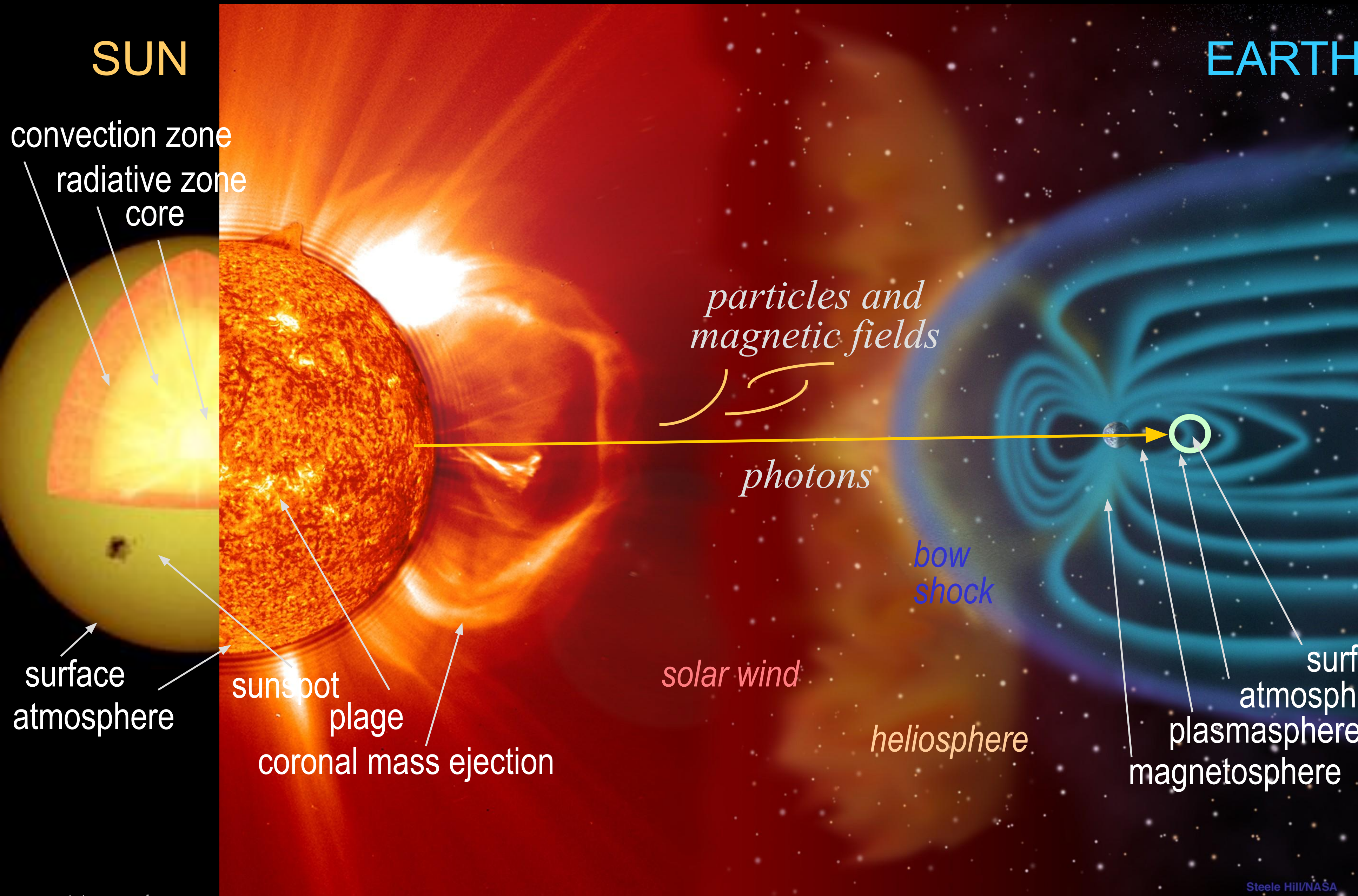
Earth’s Atmosphere

Giovanna Jerse

Summary

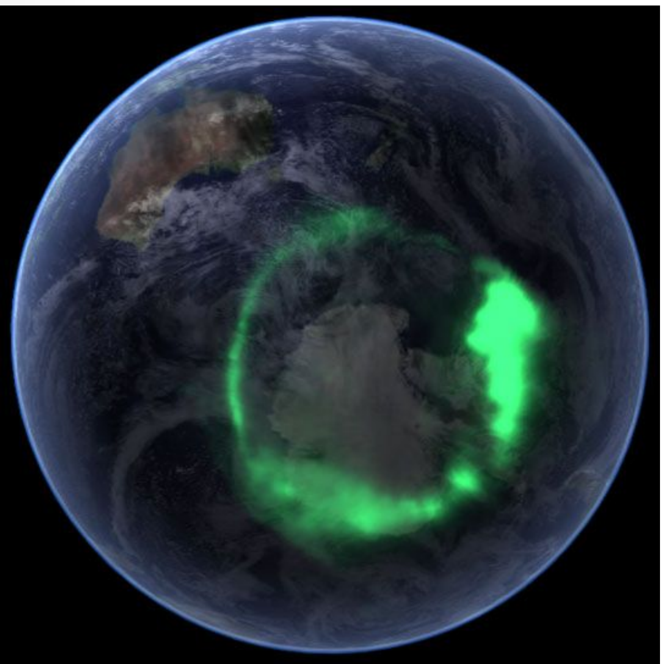
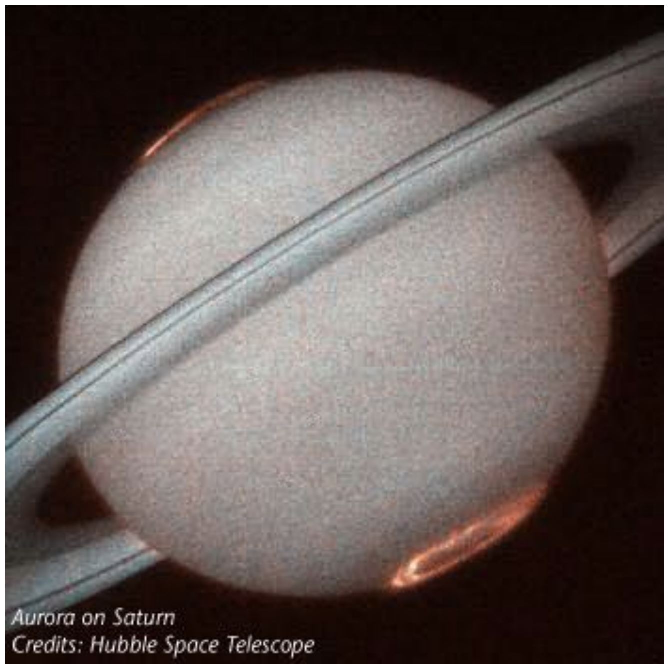
- Planetary Atmospheres
- Neutral atmosphere
- Atmospheric retention
- Ozone layer
- Atmospheric measures
- Ionosphere

Sun-Earth System: Energy Coupling



not to scale

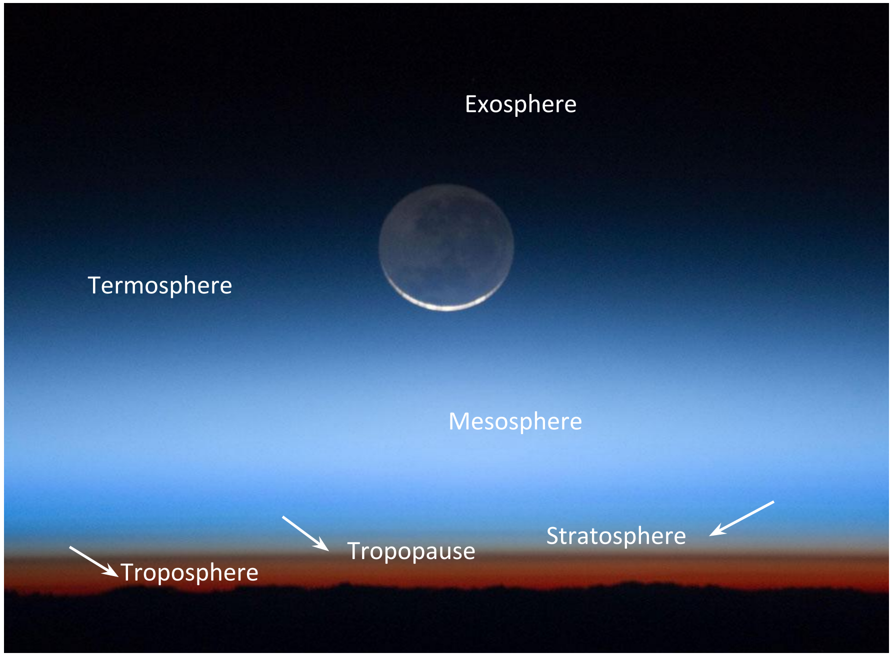




Aurora on Saturn
Credits: Hubble Space Telescope


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

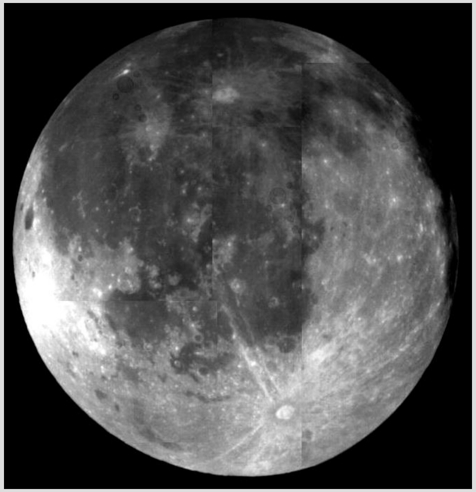
Composition of the Atmosphere Near the Earth's Surface

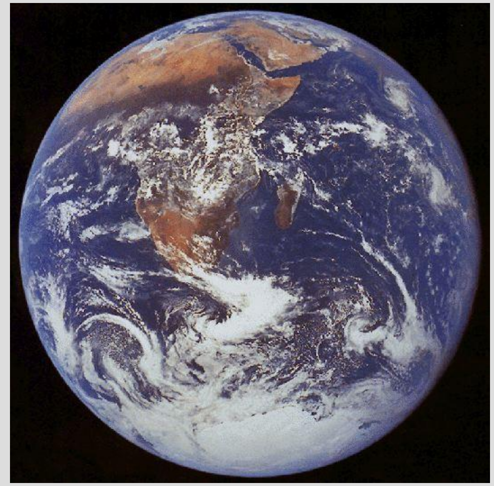
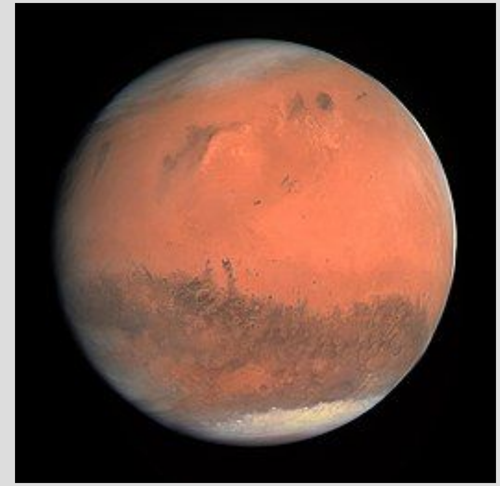
PERMANENT GASES			VARIABLE GASES			
Gas	Symbol	Percent (by Volume) Dry Air	Gas (and Particles)	Symbol	Percent (by Volume)	Parts per Million (ppm)*
Nitrogen	N_2	78.08	Water vapor	H_2O	0 to 4	
Oxygen	O_2	20.95	Carbon dioxide	CO_2	0.038	380*
Argon	Ar	0.93	Methane	CH_4	0.00017	1.7
Neon	Ne	0.0018	Nitrous 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.

Comparing Atmospheres



Atmospheric Type	Object	Main Composition	P, T at surface or 1 bar	T_∞	$\lambda_{1\,\mu bar}$	$\lambda_{exobase}$	Exobase Height (km), $r_{exobase}/r_p$	Escaping Constituents	Solar EUV, Particle/Joule Heating (10^9 W)
H_2-He atmospheres of the giant planets	Jupiter	H_2, He, CH_4, NH_3	1 bar, 165 K	900 K	2300	480	1600, 1		800, 10^5
	Saturn	H_2, He, CH_4, NH_3	1 bar, 160 K	420 K	1300	420	2500, 1		200, 200
	Uranus	H_2, He, CH_4, NH_3	1 bar, 80 K	870 K	200	50	4700, 1.2		8, 100
	Neptune	H_2, He, CH_4, NH_3	1 bar, 80 K	600 K	450	120	2200, 1.1		3, 1
Terrestrial CO_2 atmospheres	Venus	CO_2, N_2, SO_2, Ar	90 bar, 730 K	200 K	1600	35	140, 1	H	300, -
	Mars	CO_2, N_2, Ar, O_2	7 mbar, 220 K	300 K	490	200	160, 1.1	H, H_2, O, N	25, -
N_2 atmospheres	Earth	N_2, O_2, Ar, H_2O	1 bar, 280 K	1000 K	1100	130	450, 1.1	H	500, 80
	Titan	N_2, CH_4, H_2	1.4 bar, 94 K	160 K	68	45	1500, 1.6	H, H_2, N	3, < 0.2
	Triton	N_2, CO, CH_4, H_2	14 μbar, 38 K	100 K	84	23	930, 1.7	H, H_2, N	0.05, 0.1
	Pluto	N_2, CO, CH_4, H_2	3-90 μbar, 35-45 K	?	21	?	> 3000, > 3	N_2, CH_4, H, H_2	0.05, ?

Neutral atmospheric layers

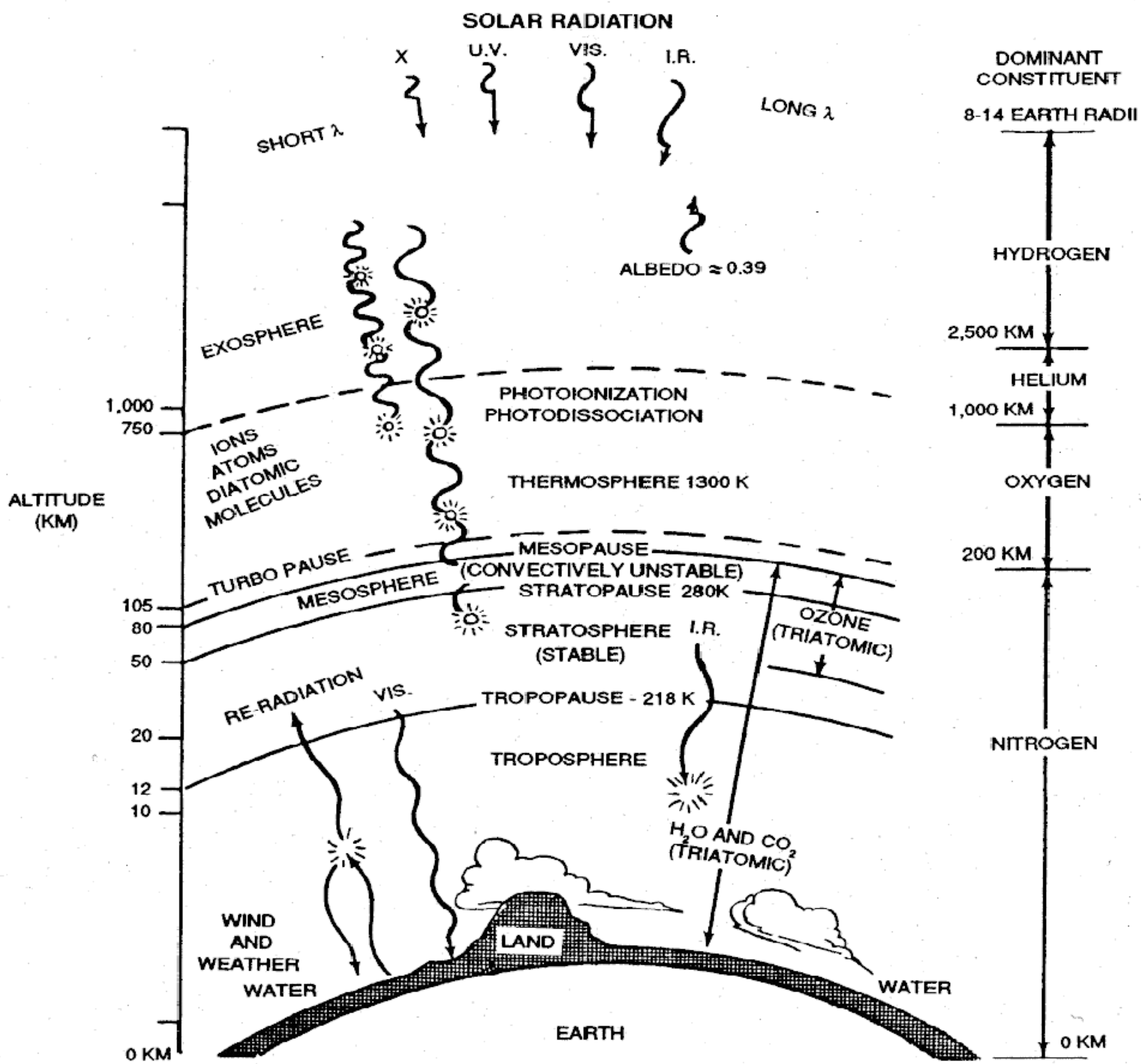
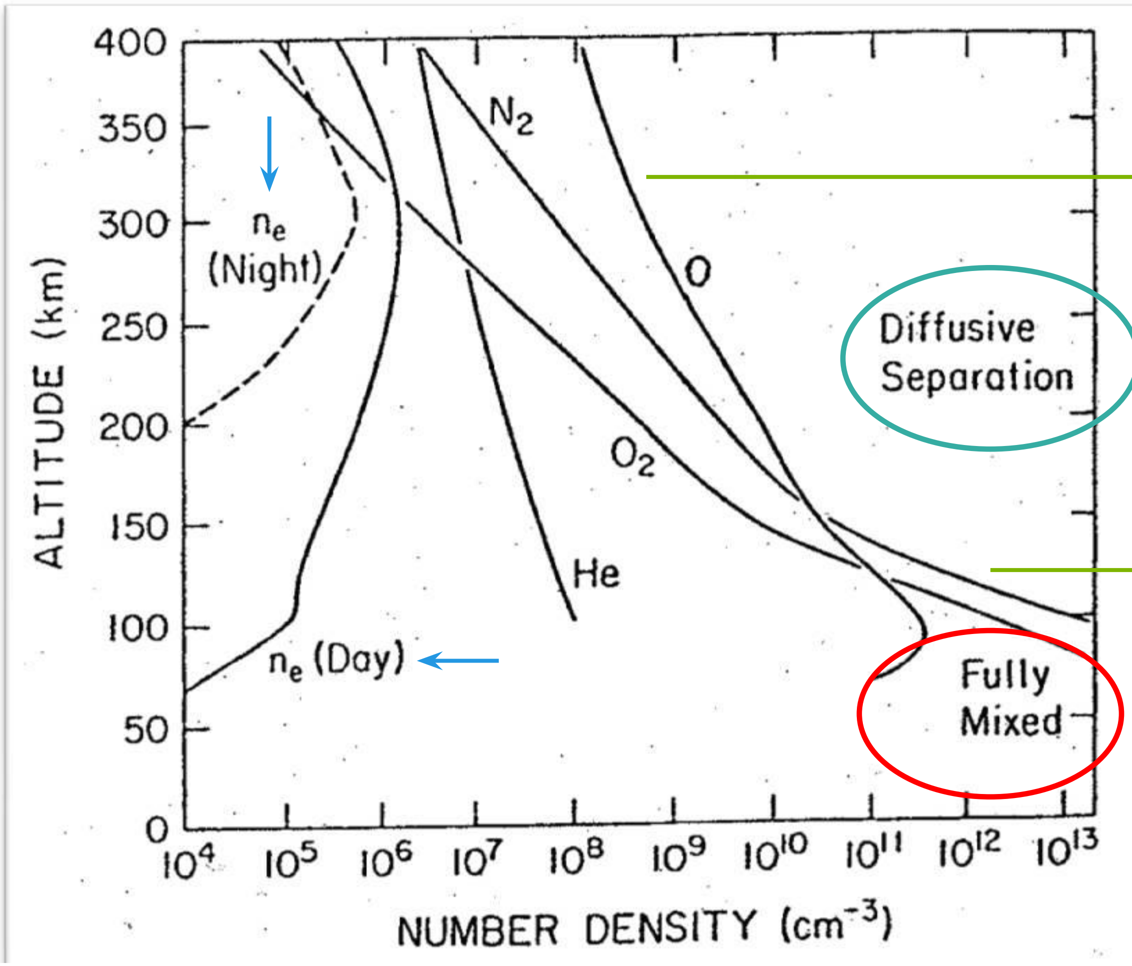


Figure 6.2 Atmospheric chemical regimes *(after Carpenter et al., 1978).*

Neutral atmosphere composition

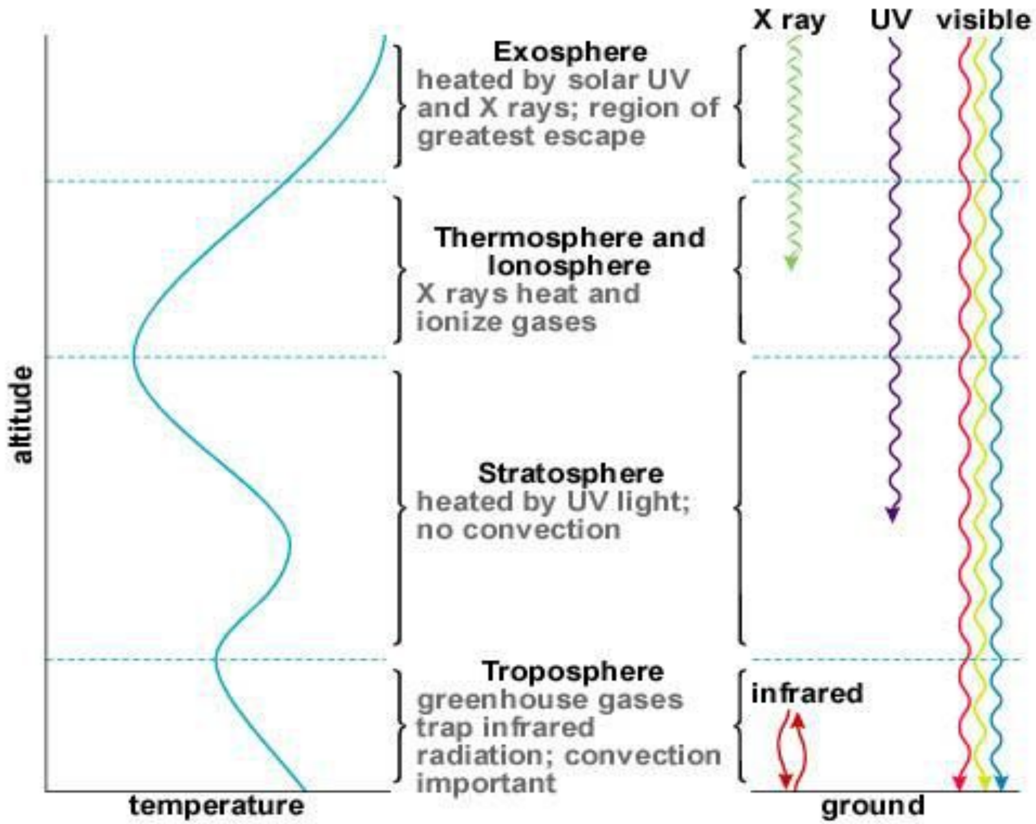
H, He dominate at highest altitude



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

N_2 dominates at low altitude

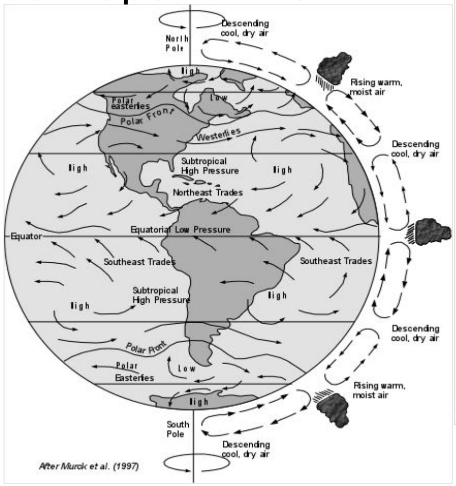
Neutral atmospheric layers

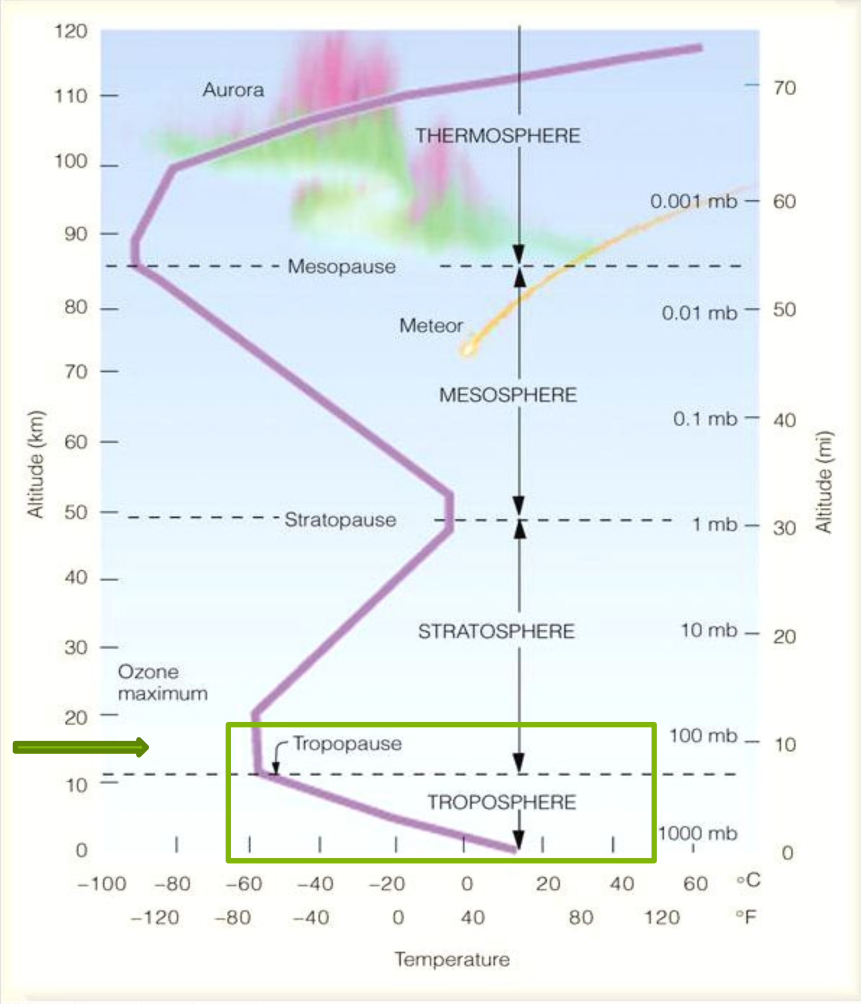


Neutral atmospheric layers

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)

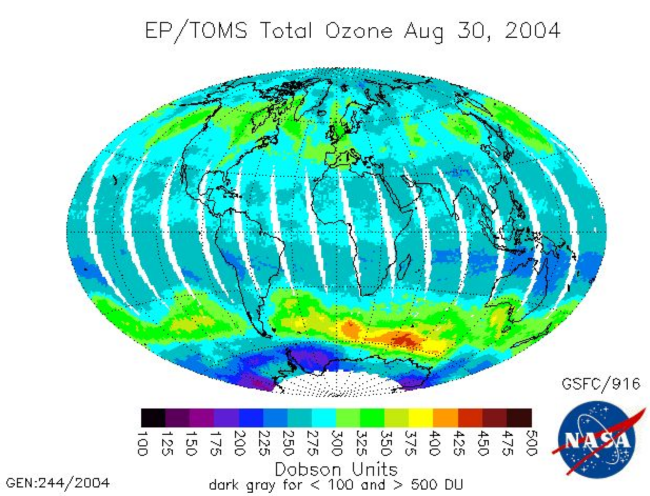


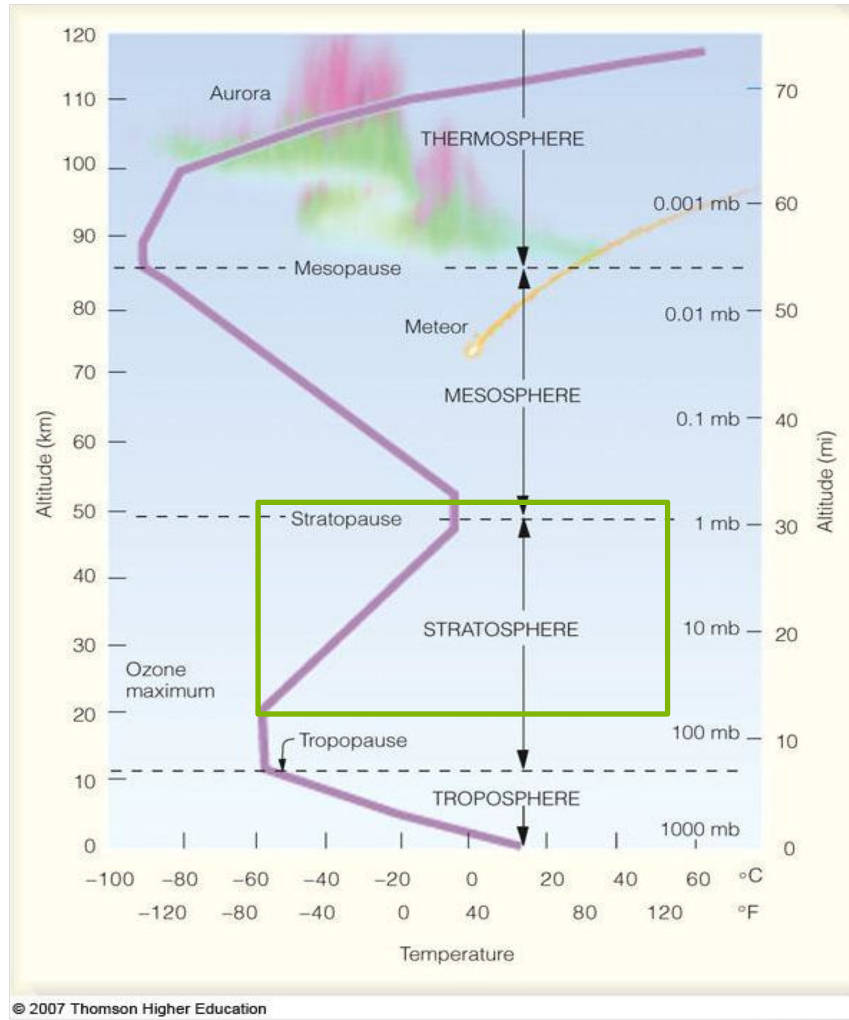


Neutral atmospheric layers

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 mesosphere and stratosphere is the stratopause.

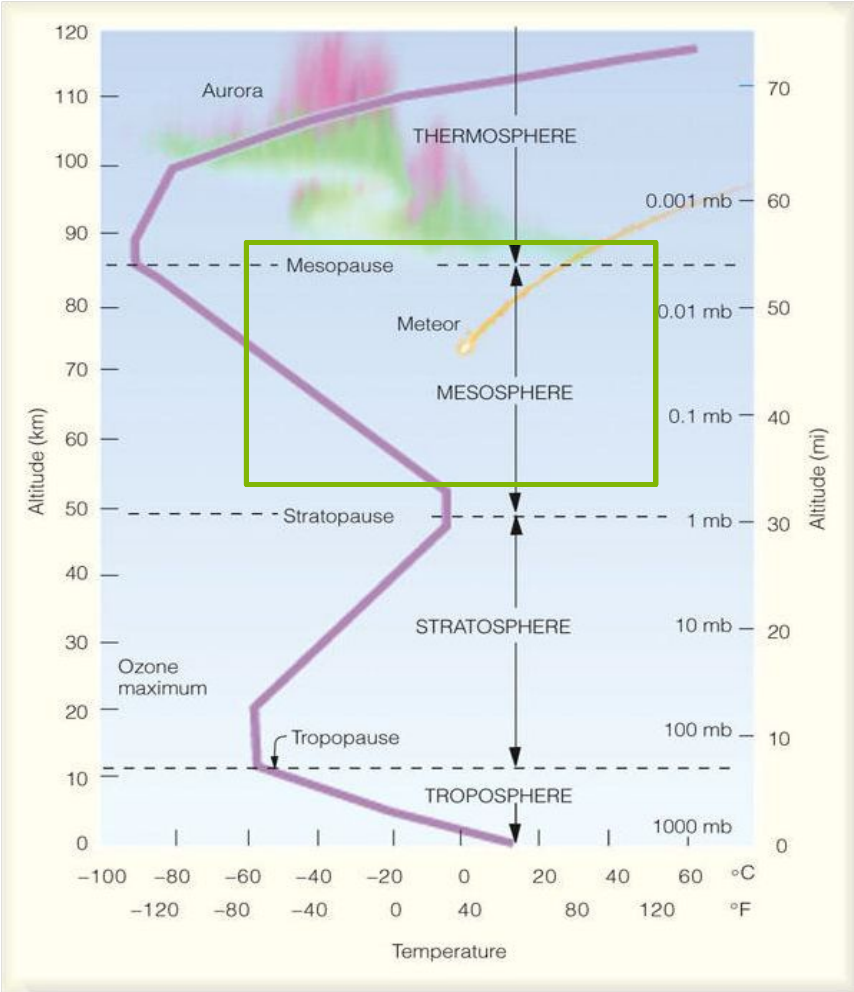




Neutral atmospheric layers

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, γ - rays)
- This layer is completely cloudless and free of water vapor
- Extremely low density (L ~ 1.6 km)
- Aurora

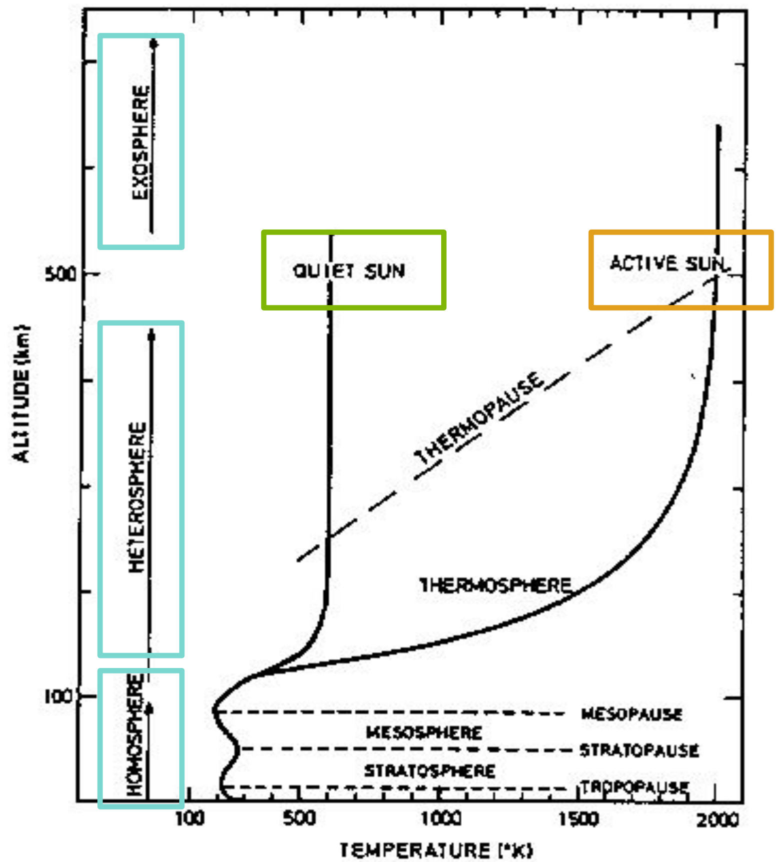


Fig 2. Vertical temperature distribution in the earth's atmosphere with emphasis on the thermosphere. (After P. M. Banks and G. Kockarts, "Aeronomy," Academic Press, New York, 1973, Part A, p. 3.)

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

Atmosphere in equilibrium

$$\text{Pressure} = \text{Net Force / Area}$$

$$\text{Force} = [P(h) - P(h+dh)] \times Area = \Delta P \times A$$

$$\text{Gravitational force} = -Mg = -\left(\frac{mass}{volume}\right) \times (A\Delta h) \times g = -\rho g \times (A\Delta h)$$

$$\Delta P \times A = -\rho g \times A\Delta h$$

$$\frac{\Delta P}{\Delta h} = -\rho g \quad \text{or, in calculus language,} \quad \boxed{\frac{dP}{dh} = -\rho g}$$

$$P = nkT = \left(\frac{\rho}{m}\right) kT$$

$$\frac{dP}{dh} = \frac{d}{dh}\left(\rho \frac{kT}{m}\right) = -\rho g$$

$$\text{If temperature} \approx \text{const}, \quad \frac{d}{dh}\left(\rho \frac{kT}{m}\right) = \frac{kT}{m}\frac{d\rho}{dh} = -\rho g$$

$$\text{Divide both sides by } \frac{kT}{\rho m}:$$

$$\frac{1}{\rho}\frac{d\rho}{dh} = -\frac{mg}{kT} = \text{const}$$

$$\boxed{\text{Solution:} \quad \rho = \rho_0 e^{-(h/h_0)} \quad \text{where} \quad h_0 = \frac{kT}{mg}}$$

Atmospheric retention

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

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

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

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

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

$T_{atm} < T_{esc}$

Atmospheric retention

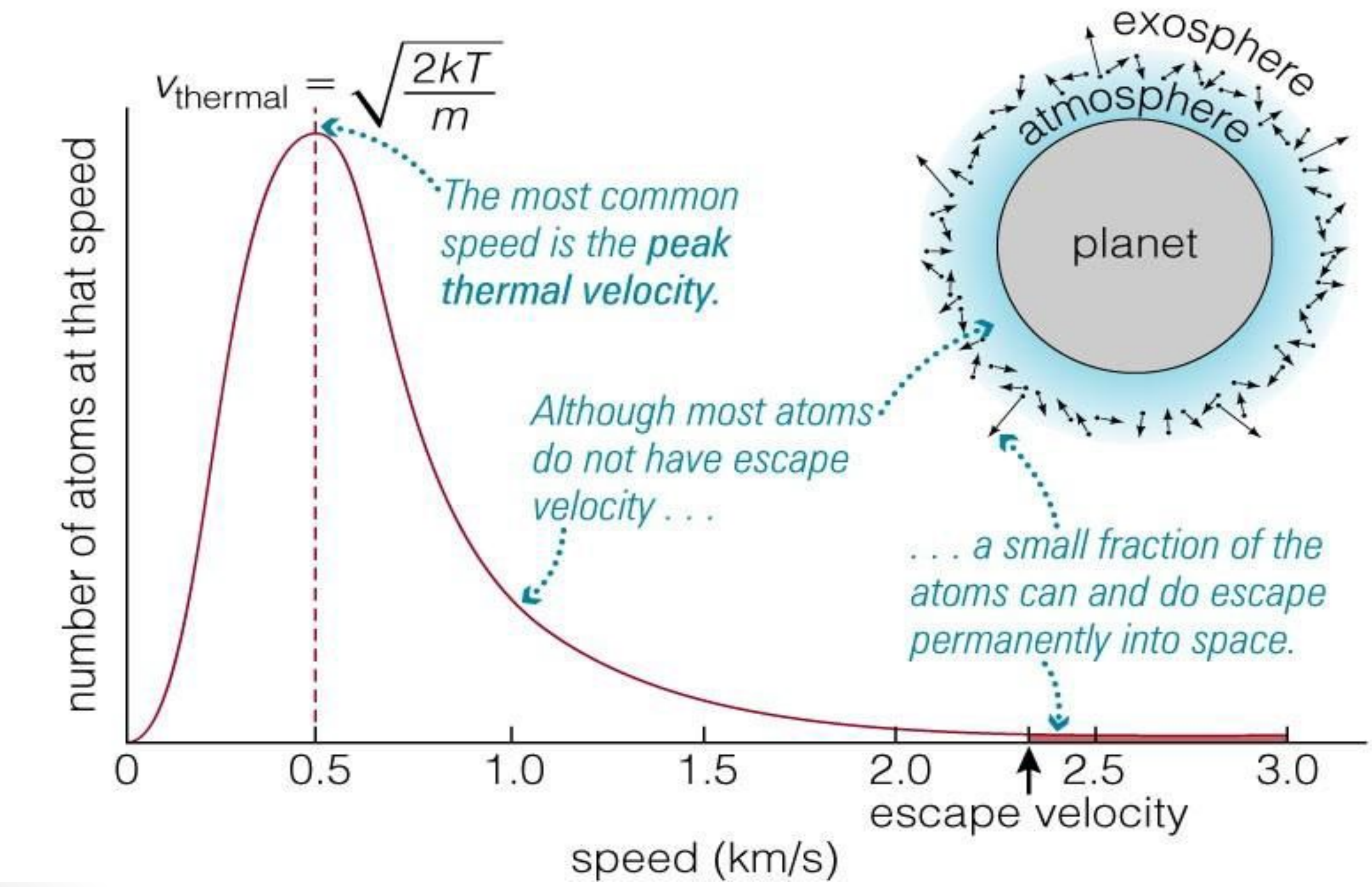
Atmospheric retention condition: the mean thermal velocity has to be several times lower than the escape velocity

$T_{atm} < T_{esc}$

Pianeta	Raggio eq. $[R_\oplus]$	Massa $[M_\oplus]$	ρ [g cm^{-3}]	v_{fuga} [km/s]
Mercurio	0.383	0.055	5.43	4.3
Venere	0.949	0.815	5.24	10.4
Terra	1.000	1.000	5.52	11.2
Marte	0.533	0.107	3.94	5.0
Giove	11.209	317.820	1.33	59.5
Saturno	9.449	95.161	0.70	35.5
Urano	4.007	14.371	1.30	21.3
Nettuno	3.883	17.147	1.76	23.7

$R_\oplus = 6378$ km ; $M_\oplus = 5.974 \times 10^{27}$ g

Atmospheric retention



Equilibrium Temperature

Equilibrium or steady state: balance W/m^2 = joules/sec per m^2

W/m^2 absorbed from sunlight $= W/m^2$ emitted in thermal radiation

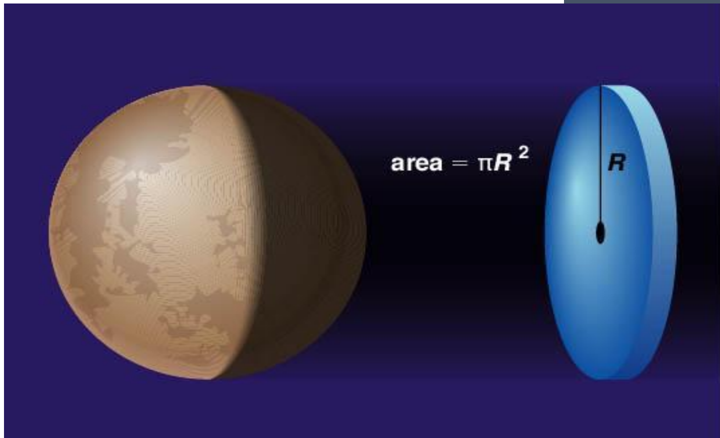
Scale to Earth: incident power from Sun $= 1{,}360\ \frac{W}{m^2}$ at top of atmosphere

$$1{,}360\ \frac{W}{m^2} \times \left(\frac{1\ \text{AU}}{\text{dist. from Sun}}\right)^2 \times \pi \left(R_{planet}\right)^2 \times (1 - albedo) = \sigma T^4 \times 4\pi \left(R_{planet}\right)^2$$

Solve for T:

$$T = \left[\frac{1{,}360\ W/m^2 \times (1 - albedo)}{4\sigma\,(\text{dist. from Sun}/1\ \text{AU})^2}\right]^{1/4} = 280K \left[\frac{1 - albedo}{(\text{dist. from Sun}/1\ \text{AU})^2}\right]^{1/4}$$

albedo = fraction of sunlight that is reflected by a surface



Total energy leaving Sun:

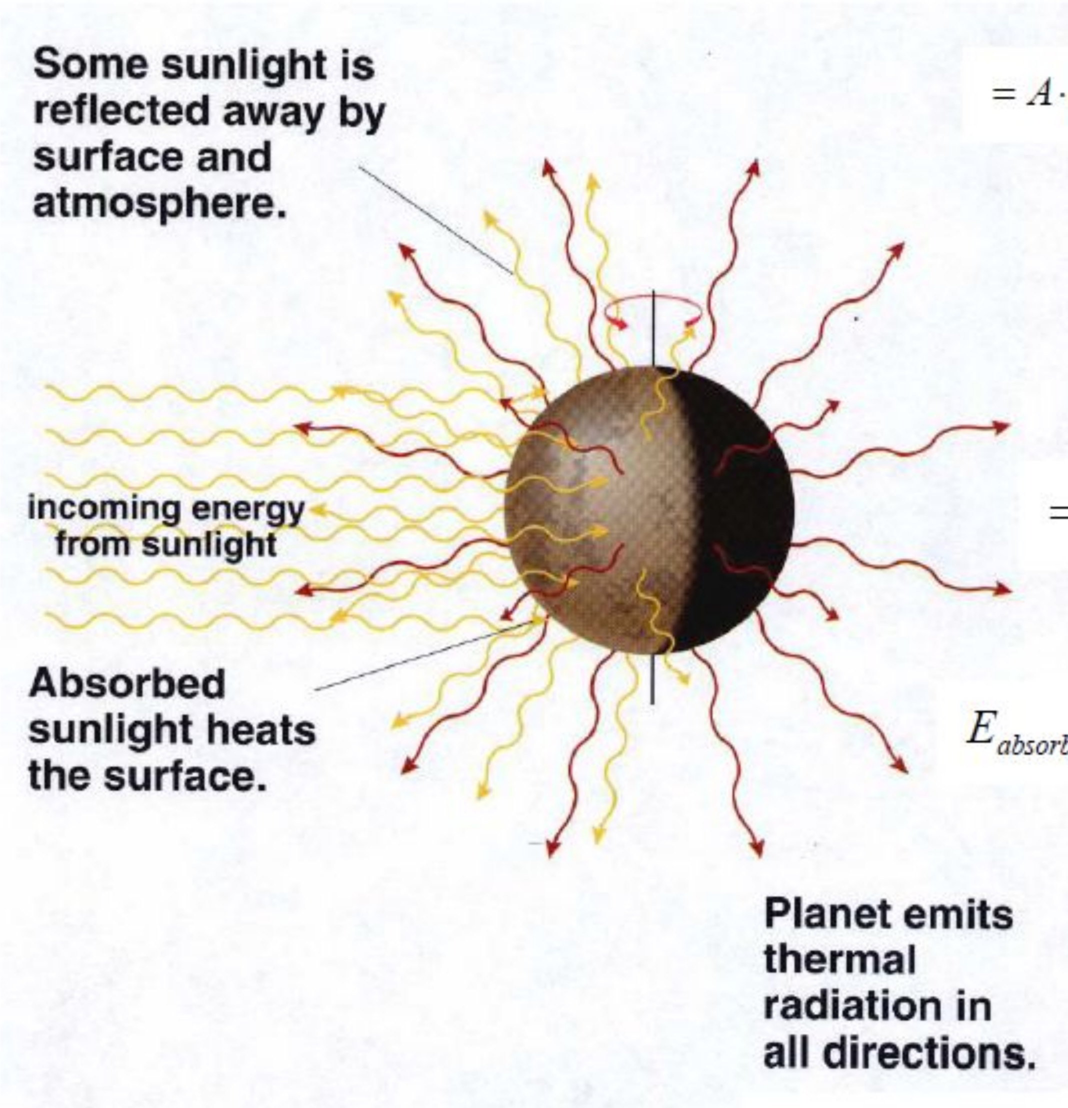
$$E_{tot}(sun) = \sigma \cdot T^4{}_{sun} \cdot 4\pi R^2{}_{sun}$$

Energy reaching planet at d (AU): $E_p = \dfrac{E_{tot}}{4\pi \cdot d^2} = \dfrac{\sigma \cdot T^4{}_{sun} 4\pi R^2{}_{sun}}{4\pi \cdot d^2}$

Some reflected: 40%
(Albedo = A)

Some absorbed: 60%
(1 – Albedo = 1 – A) $\Rightarrow$ $E_p \cdot \pi \cdot R^2{}_{planet}(1 - A)$

$$= A \cdot E_p \cdot \pi \cdot R^2{}_{planet}$$



$$= E_p \cdot \pi \cdot R^2{}_{planet}$$

$$E_{absorbed} = E_p \cdot \pi \cdot R^2{}_{planet}(1 - A)$$

$$E_{radiated} = \sigma \cdot T^4{}_{planet} \cdot 4\pi \cdot R^2{}_{planet}$$

Equilibrium condition: $E_{radiated} = E_{absorbed}$

So we have: $$\sigma \cdot T^4 = \frac{\sigma \cdot T^4{}_{sun}}{4\pi \cdot d^2} \cdot \frac{4\pi \cdot R^2{}_{sun}}{4\pi \cdot R^2{}_{planet}} \cdot \pi \cdot R^2{}_{planet}(1-A)$$

$$\Rightarrow \quad T_{planet} = \left[\frac{R^2{}_{sun}}{d^2} \cdot \frac{1-A}{4}\right]^{\frac{1}{4}} \cdot T_{sun}$$

The temperature of a planet does not depend on its radius.

Note: for a rapidly rotating planet, the effective area of intercept is $2\pi \cdot R^2{}_{planet}$

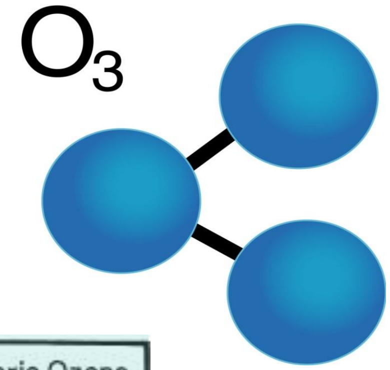
Questions

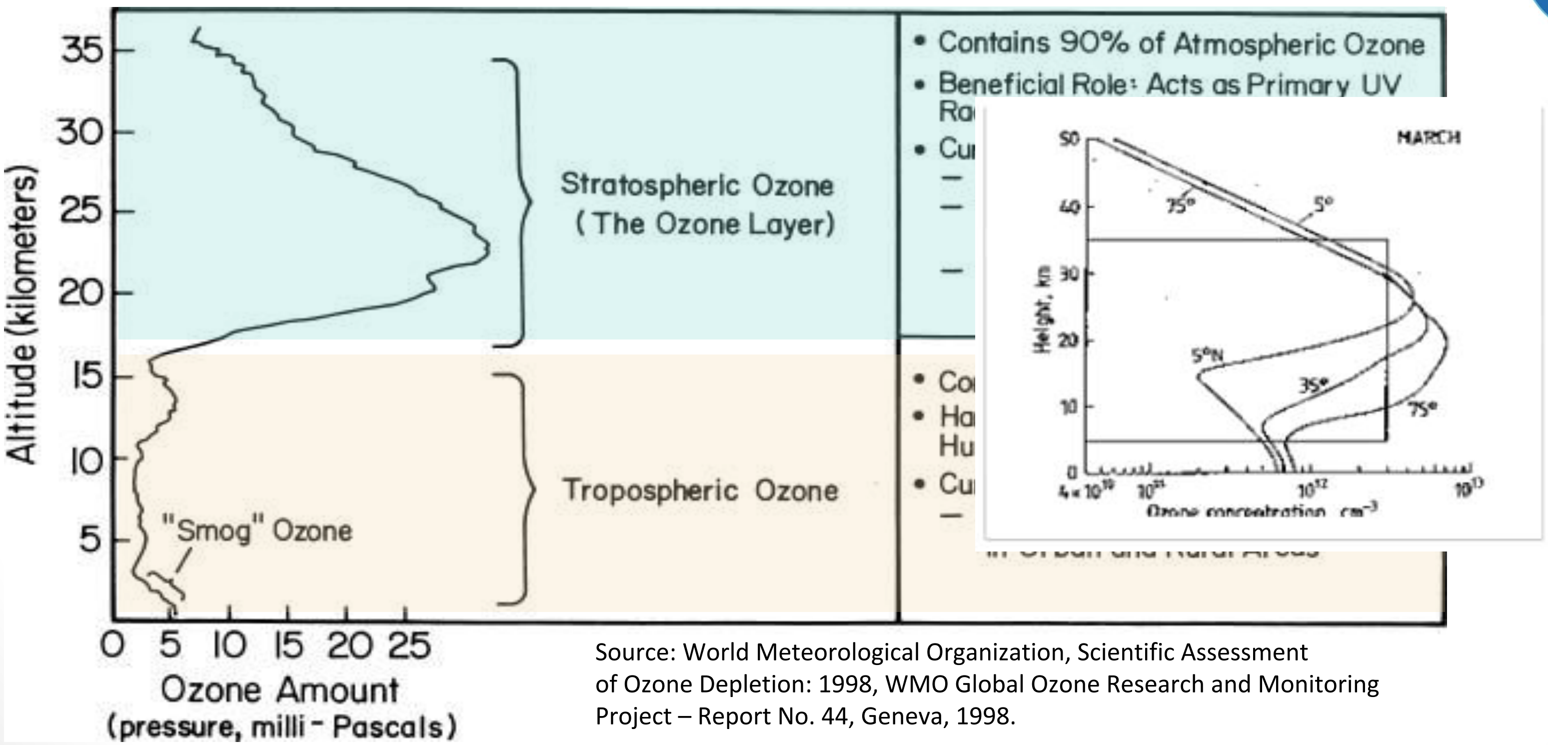
1. Why does the Earth have an atmosphere and Mercury and the Moon doesn't? Why does Titan have an atmosphere?
2. Determine the mass of the Atmosphere?
3. Determine the scale heights and the effective temperature(see table); compare with the real temperature, conclusions?
4. Faint Young Sun Paradox

Planet	Temp[K]	g[m/s2]	Composition	Average distance from Sun	Albedo
Venus	700	8,87	97% CO_2; 3% N_2	0.72	0.71
Earth	288	9,81	22% O_2; 78% N_2	1	0.28
Mars	210	3,71	100% CO_2	1.52	0.17
Jupiter	124	22,88	90% H_2; 10% He	5.2	0.73
Titan	94	1,35	100% N_2		

Atmospheric Ozone

- Ozone is a gas made up of three oxygen atoms (O_3).
- ρ ~ 0.001% in volume
- Absorb UV radiation (λ = 200 – 315 nm), Ozone peak absorption at λ ~ 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* $O_2 + \text{light} \longrightarrow 2O$ (120 – 210 nm)
- *Propagation* (cycling)

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

  $O_3 + \text{light} \longrightarrow O_2 + O$ (220 – 320 nm)

- *Termination* $O_3 + O \longrightarrow 2O_2$

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

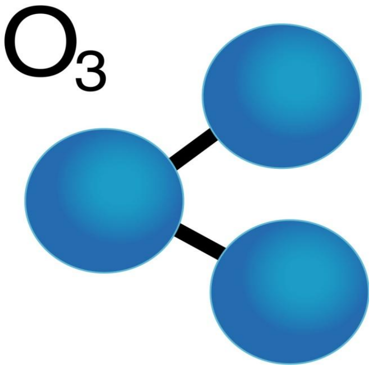
Predicts too much ozone

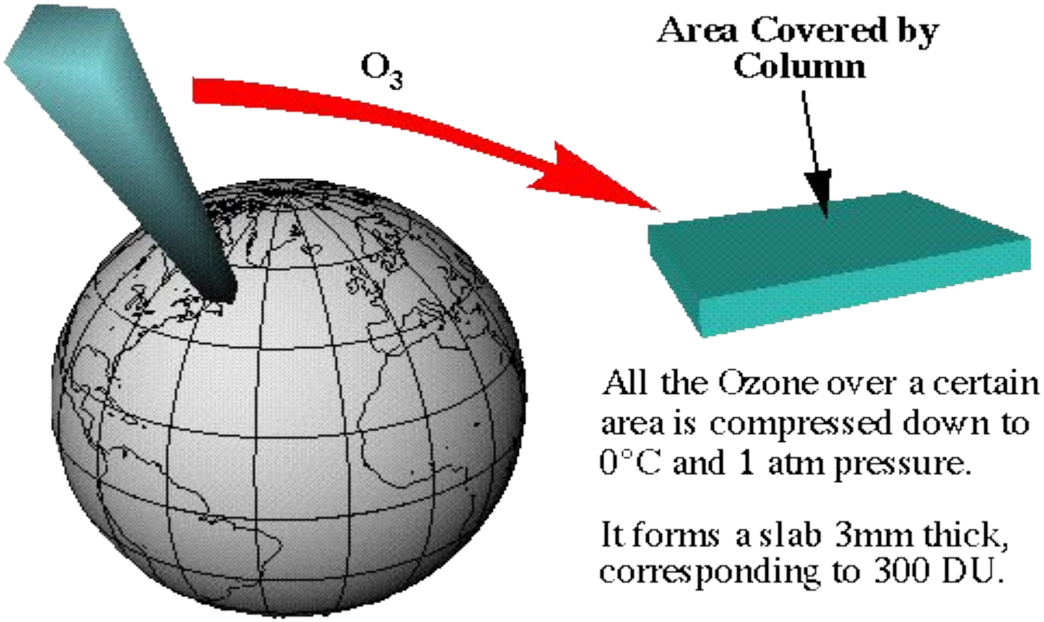
Atmospheric Ozone

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

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

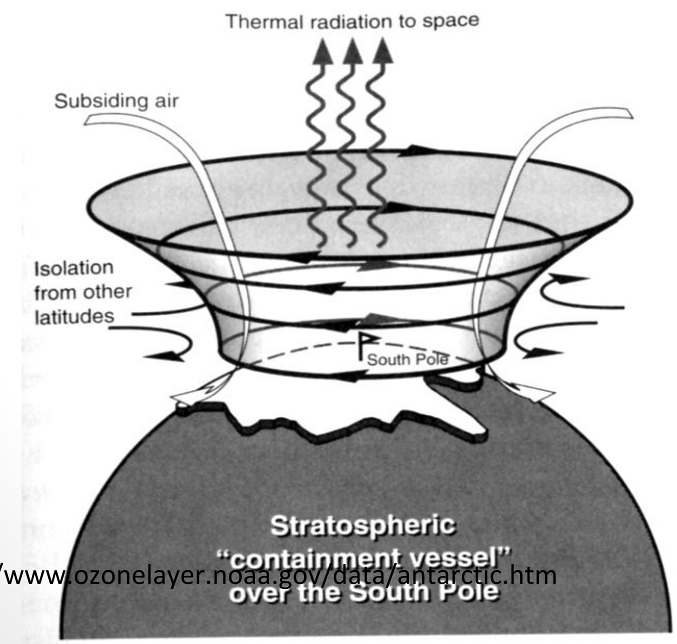
- 300 DU = standard mean Ozone concentration
- Geographic area with **less than 220 DU** = Ozone hole



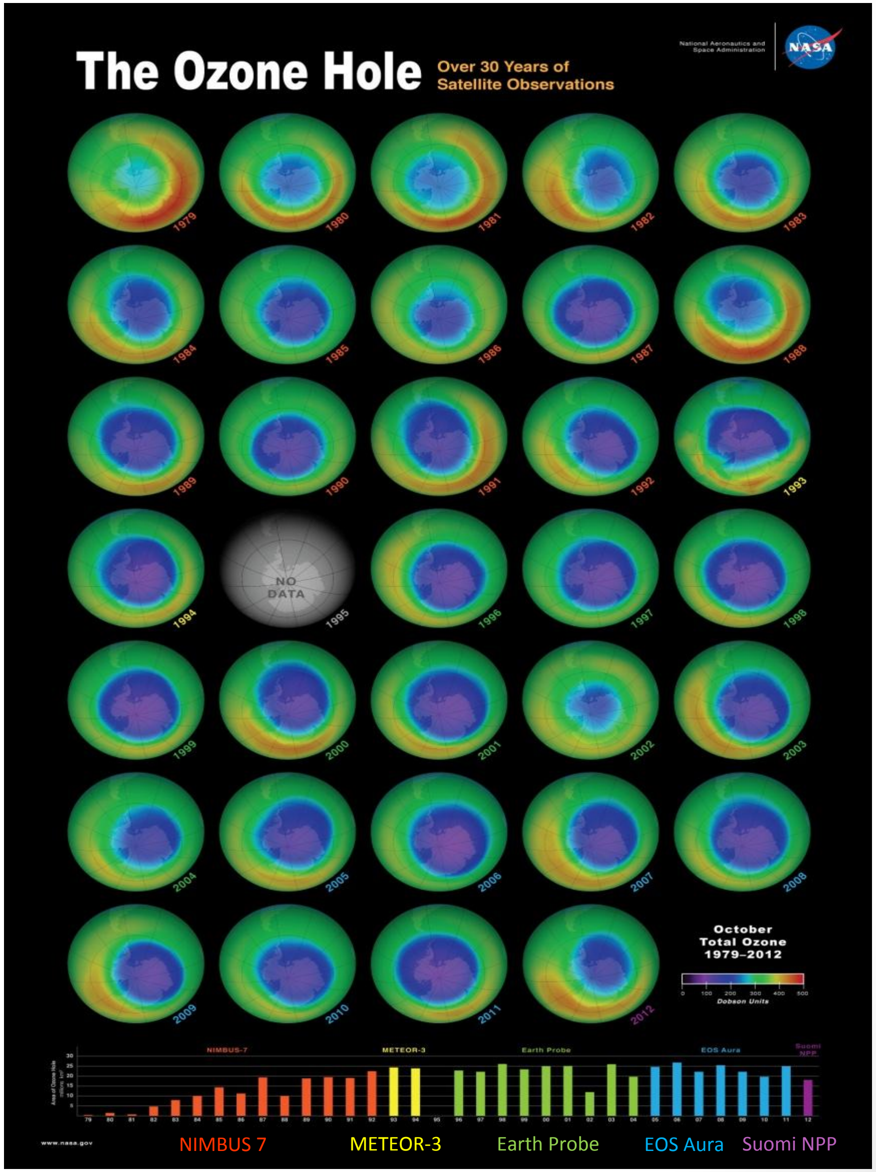


Atmospheric Ozone depletion

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



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



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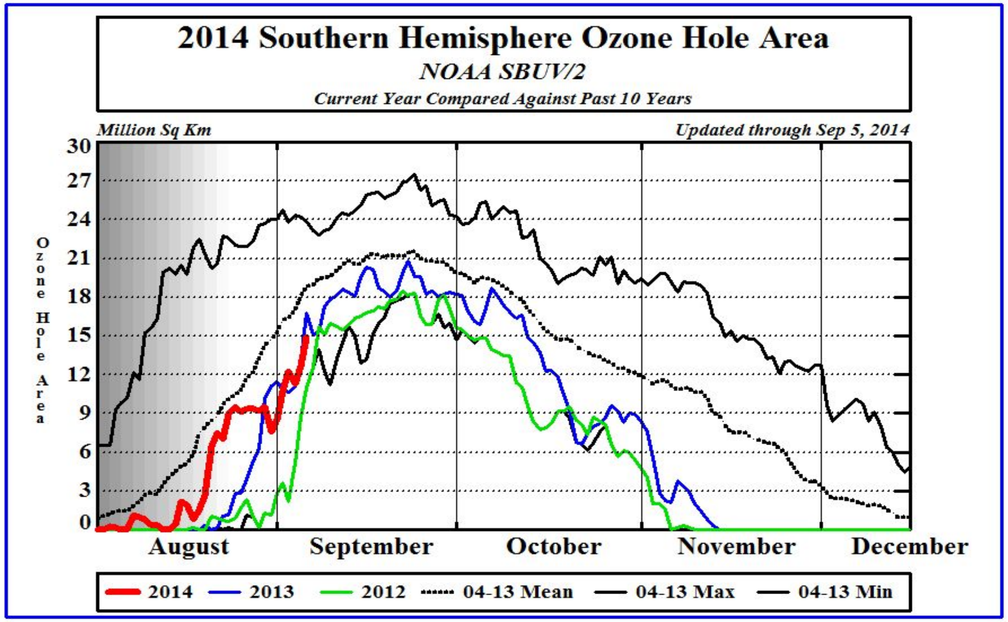

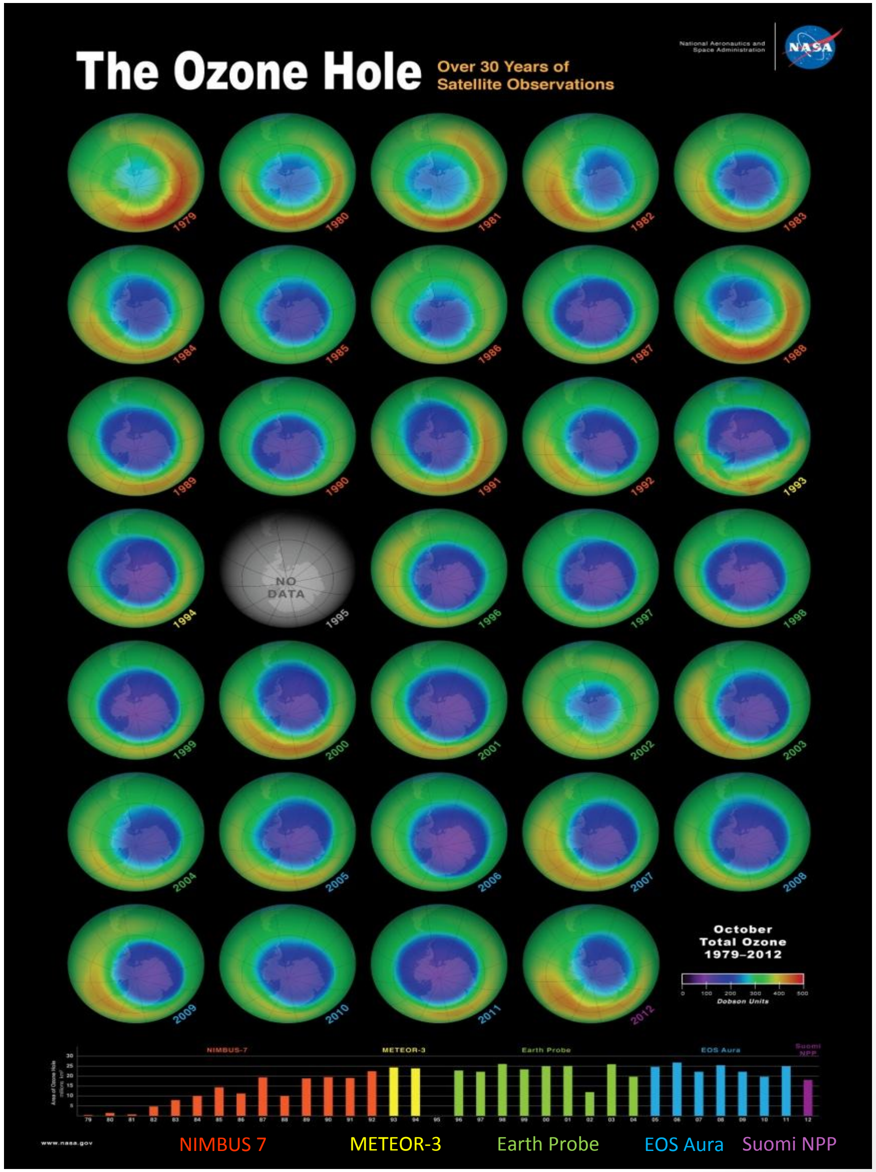

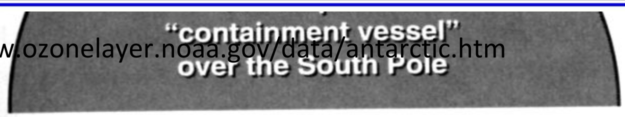

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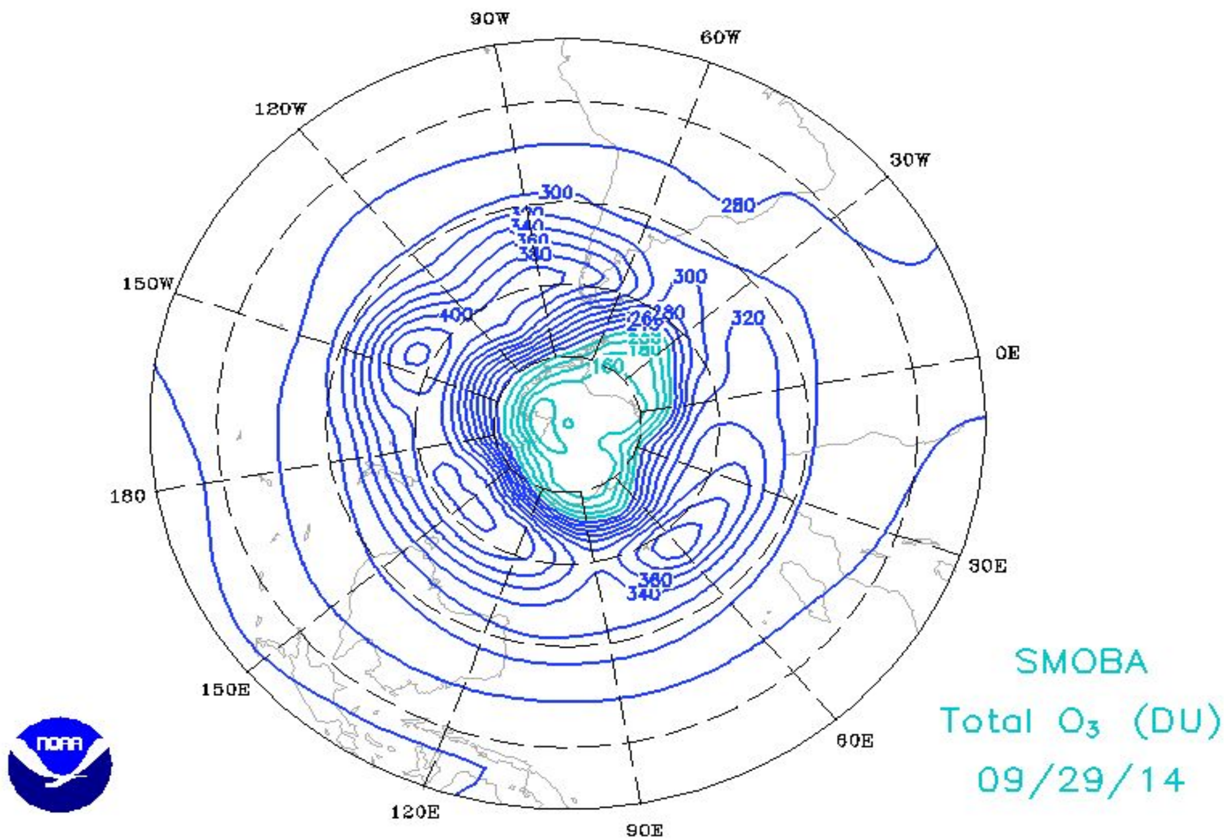
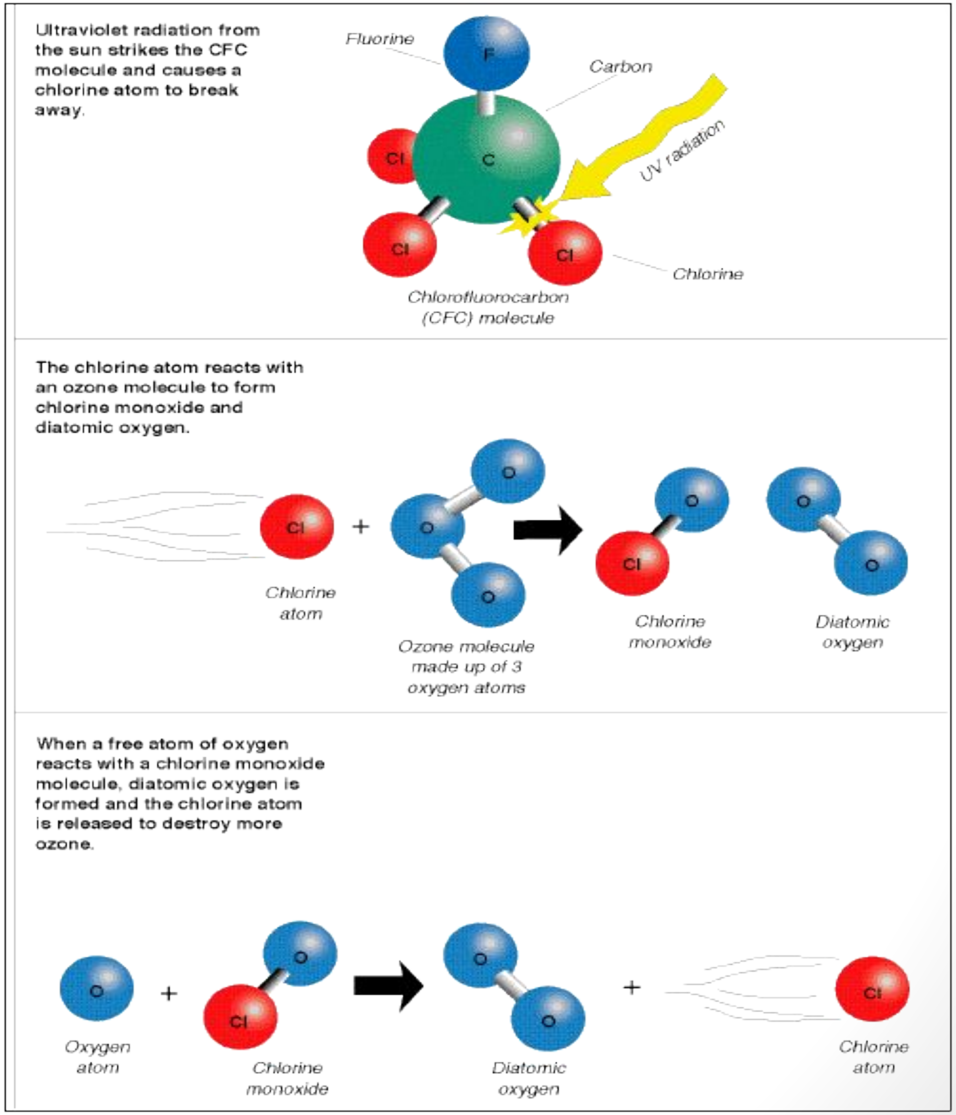


CFCs interaction with O_3

- 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**

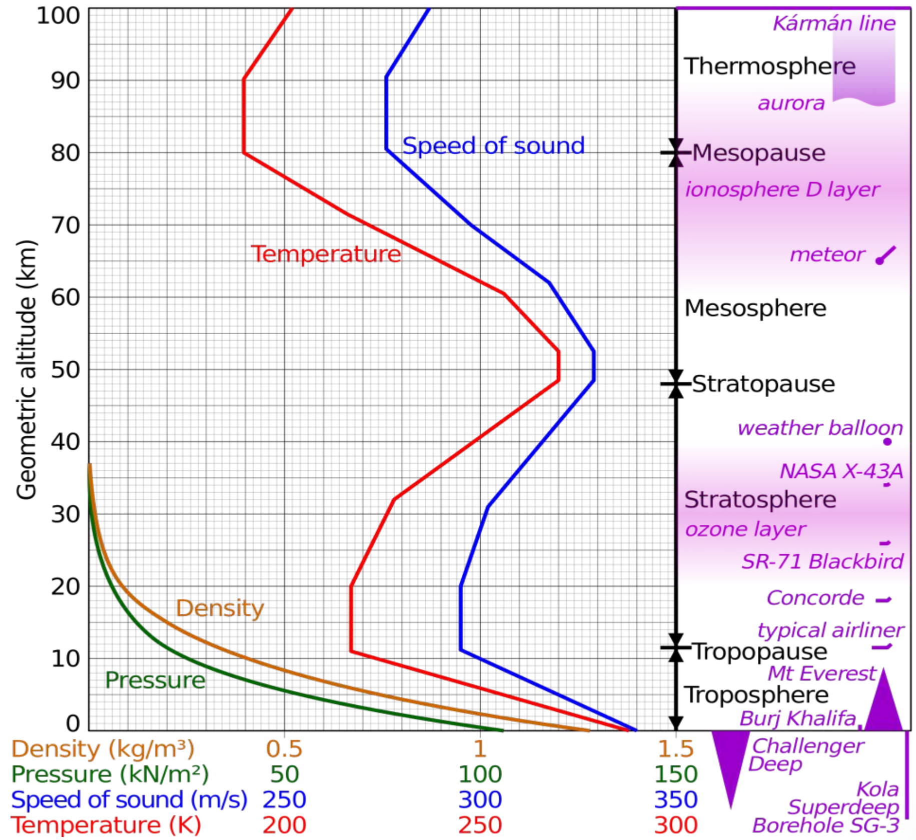


SOLAR - TERRESTRIAL ENERGY SOURCES

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 lll	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

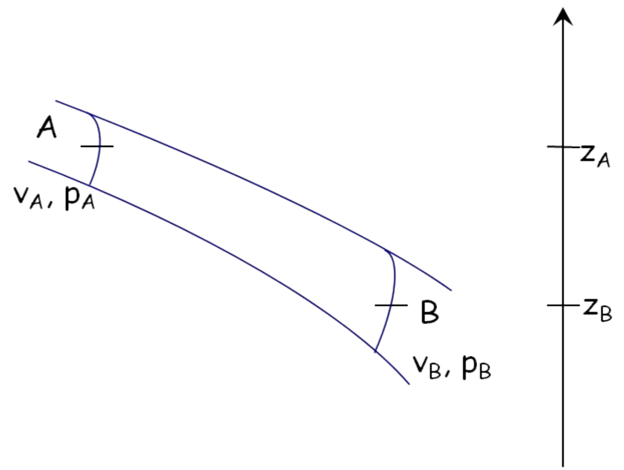
Atmospheric measures: ρ, v, T

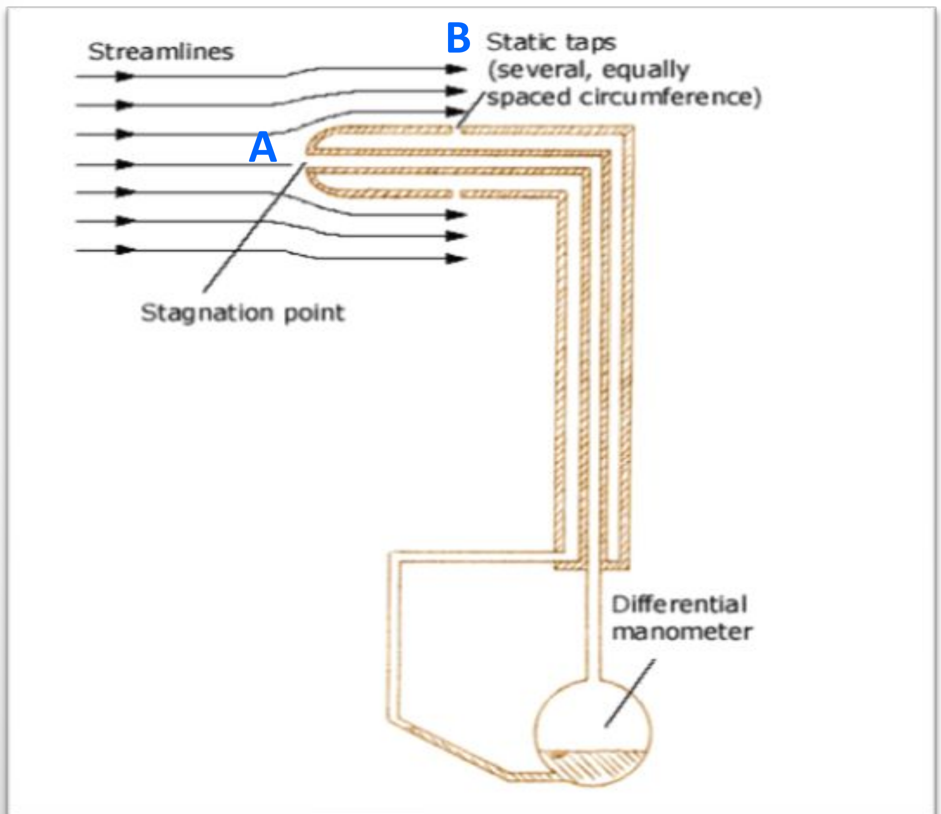
- Balloons (30 ÷ 35 km)
- Sounding rocket (40 ÷ 200 km)
  - Explosions
  - Release of tracer (Na)
  - Pitot tubes
  - Barometric Equation
- Satellite
  - Orbital Measures
  - Instruments



Pitot tube

- Eq. Bernoulli
- $p_A + \rho g z_A + \rho v_A^2/2 = p_B + \rho g z_B + \rho v_B^2/2 = \text{cost}$





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

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

$\quad = GM/R_T^{\,2}\; mR_T^{\,2} / (R_T+h)^2 = m\,g0R_T^{\,2}/(R_T+h)^2 =$

$\Rightarrow g' = g0\, R_T^{\,2} / (R_T+h)^2$

$E \quad = mg'h = mhg0R_T^{\,2}/(R_T+h)^2 = mg0h'$

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

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

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

$\Rightarrow \ln(n_1/n_2) = -mg0(h_1'-h_2')/kT = -d/D$ eq. Barometrica

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

EXERCISE 2

- For a given molecule to be retained: $$\sqrt{\frac{2GM}{R}} > \sqrt{\frac{3kT}{m}} \Rightarrow m > \frac{3kTR}{2GM}$$

- ***Definition:*** $m = \mu\, m_H$
  - where μ is molecular weight and m_H is mass of H-atom ($m_H = 1.67 \times 10^{-27}$ kg).
  - so, for hydrogen $\mu = 1$, and for helium $\mu = 4$
  - hence at a given temperature the He atoms will be moving slower than H atoms

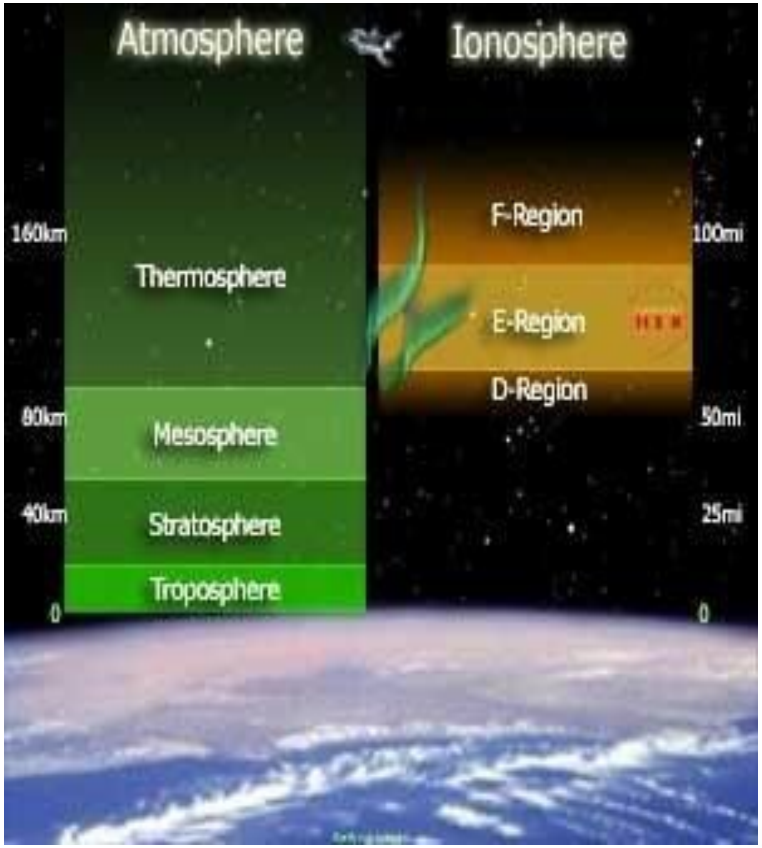
- ***For Earth***
  - $T_{atm} = 288\ K$ and $v_{esc} = 11.2\ km\ s^{-1}$
  - Hence, escape for all molecules with $\mu \leq 4$
  - So, don't expect to find much H or He.

- ***For Jupiter***
  - $T_{atm} = 134\ K$ and $v_{esc} = 59.5\ km\ s^{-1}$
  - Hence, escape for all molecules with $\mu < 0.06$
  - So, nothing escapes, since hydrogen with $\mu = 1$ is the 'lightest' gas element. Observations show that Jupiter is a H and He gas giant.

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' coined by Watson in 1926
- First evidence of an ionosphere on a planet othen than earth: Venus , 1967, measurement by mariner 5

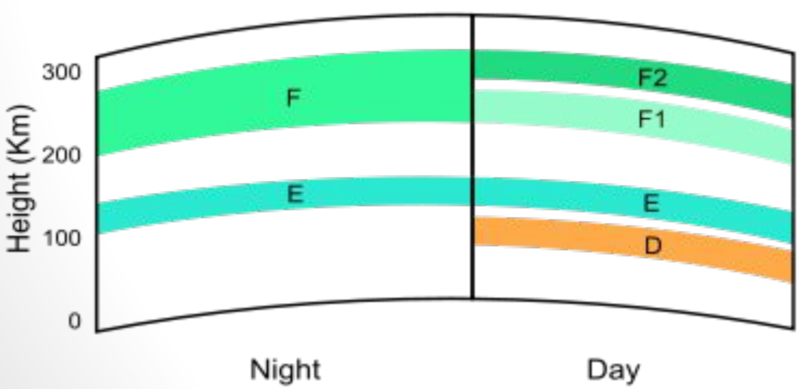


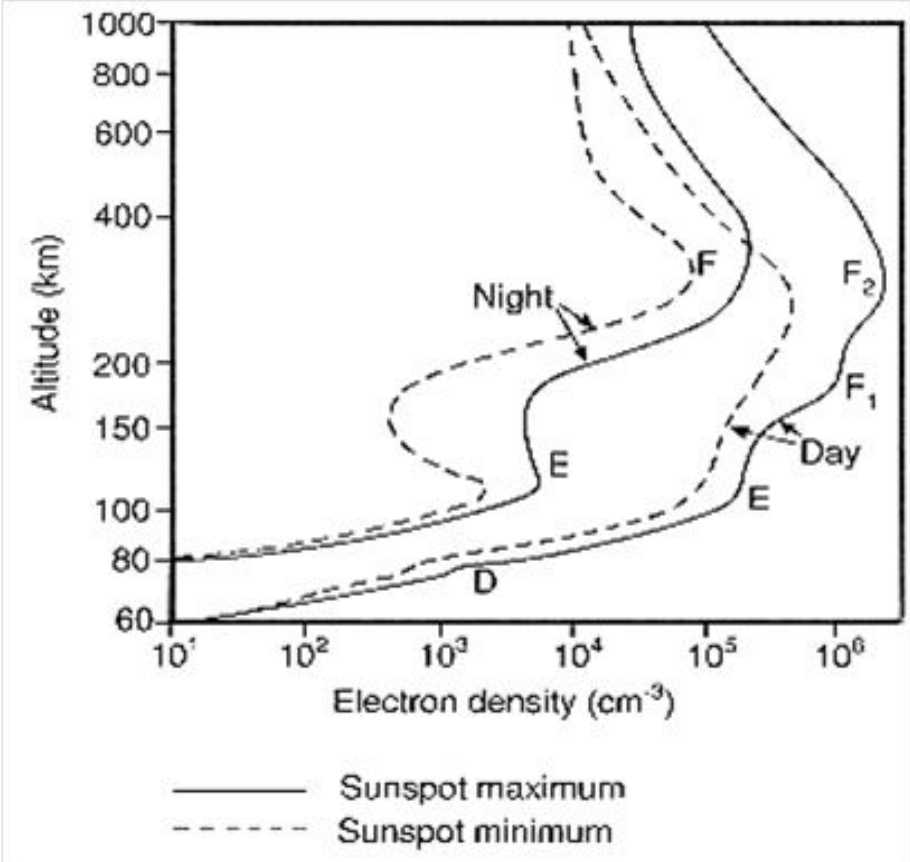
Why is Study of Ionosphere Importa

- 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

Ionosphere

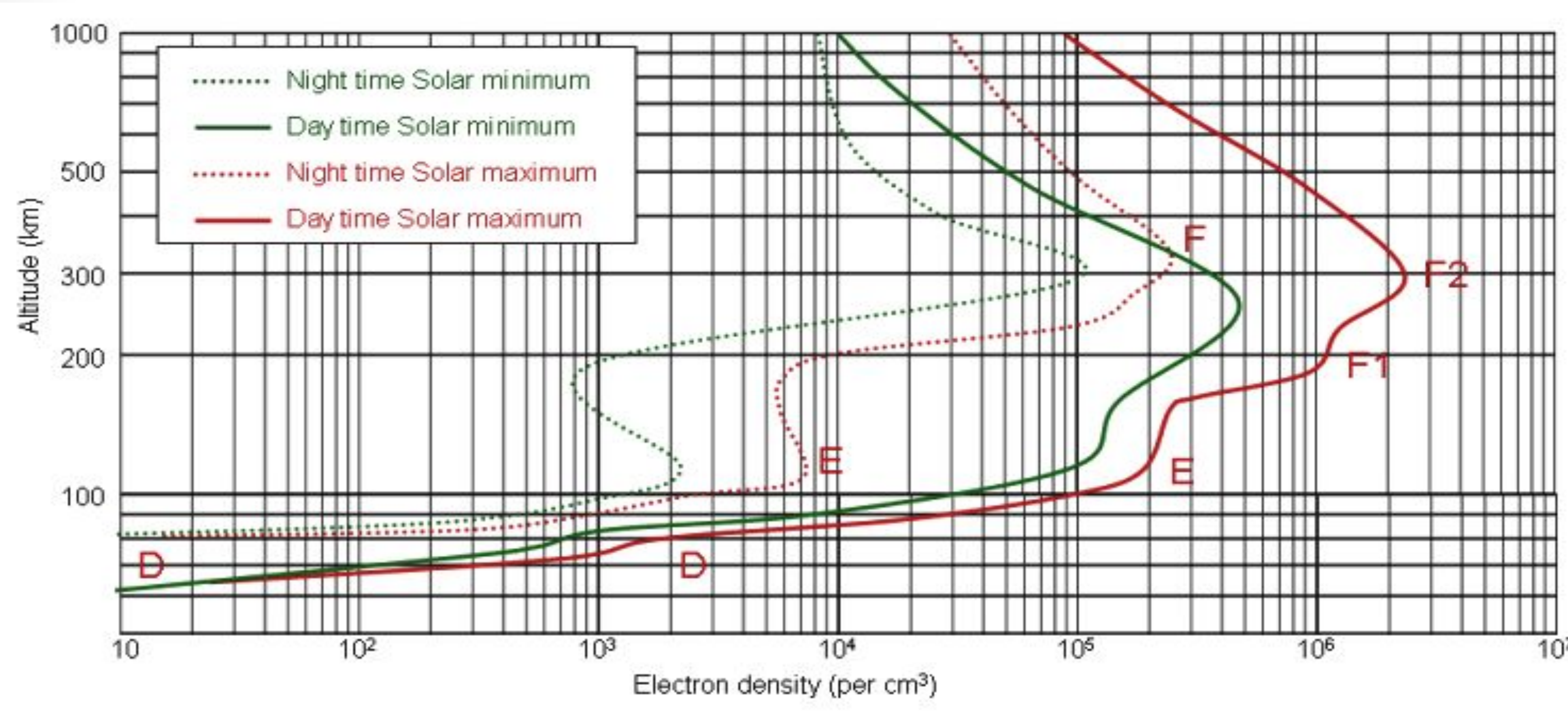
- Day – night variation
- Solar activity influence
- Ion/neutral ratio (n/n_n) (Weak ionization)
  - 10^{-8} at 100 km
  - 10^{-3} at 300 km
  - 10^{-2} at 1000 km





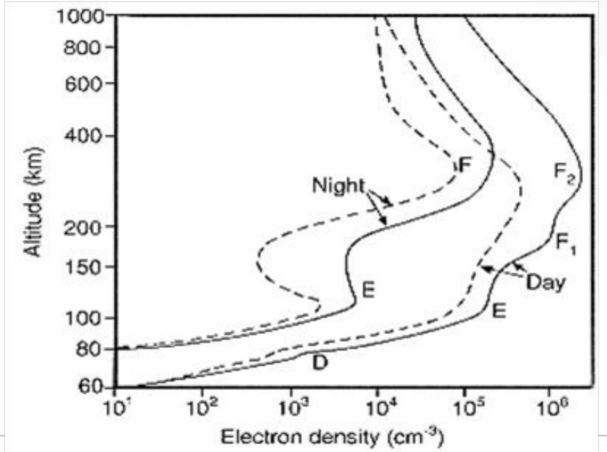
- D region (≈60–90 km, peaks around 90 km);
- E region (≈90–140 km, peaks around 110 km);
- F_1 region (≈140–200 km, peaks around 200 km);
- F_2 region (≈200–500 km, peaks around 300 km);
- Topside ionosphere (above the F_2 region).

Ionosphere: solar activity variations



Ionospheric Composition

- Composition of the dayside ionosphere under solar minimum conditions.
  - At <u>low altitudes</u> the major ions are $\mathbf{O_2^+}$ and $\mathbf{NO^+}$
  - Near the <u>F_2 peak</u> it changes to $\mathbf{O^+}$
  - The <u>topside</u> ionosphere becomes $\mathbf{H^+}$ 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.



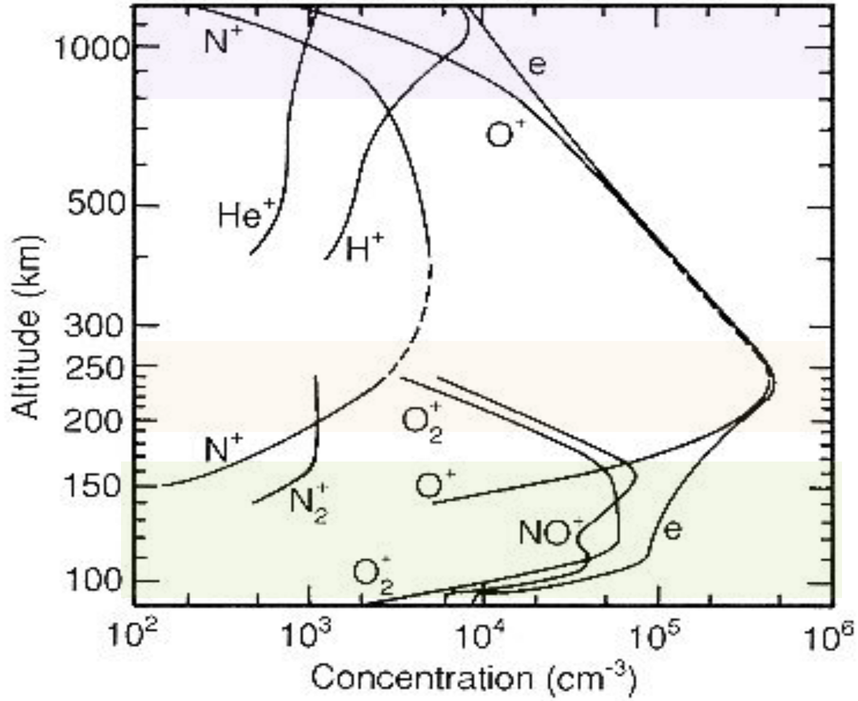
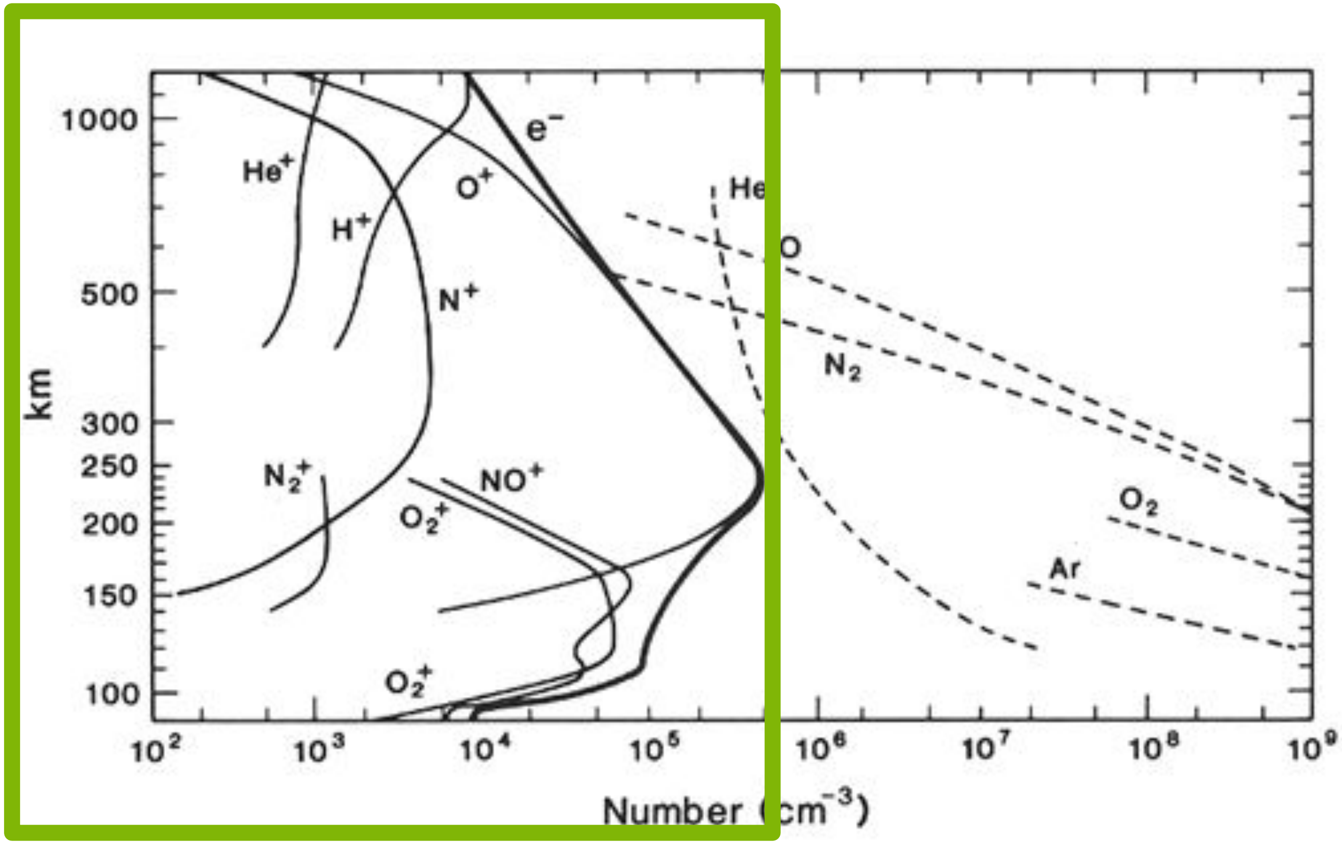


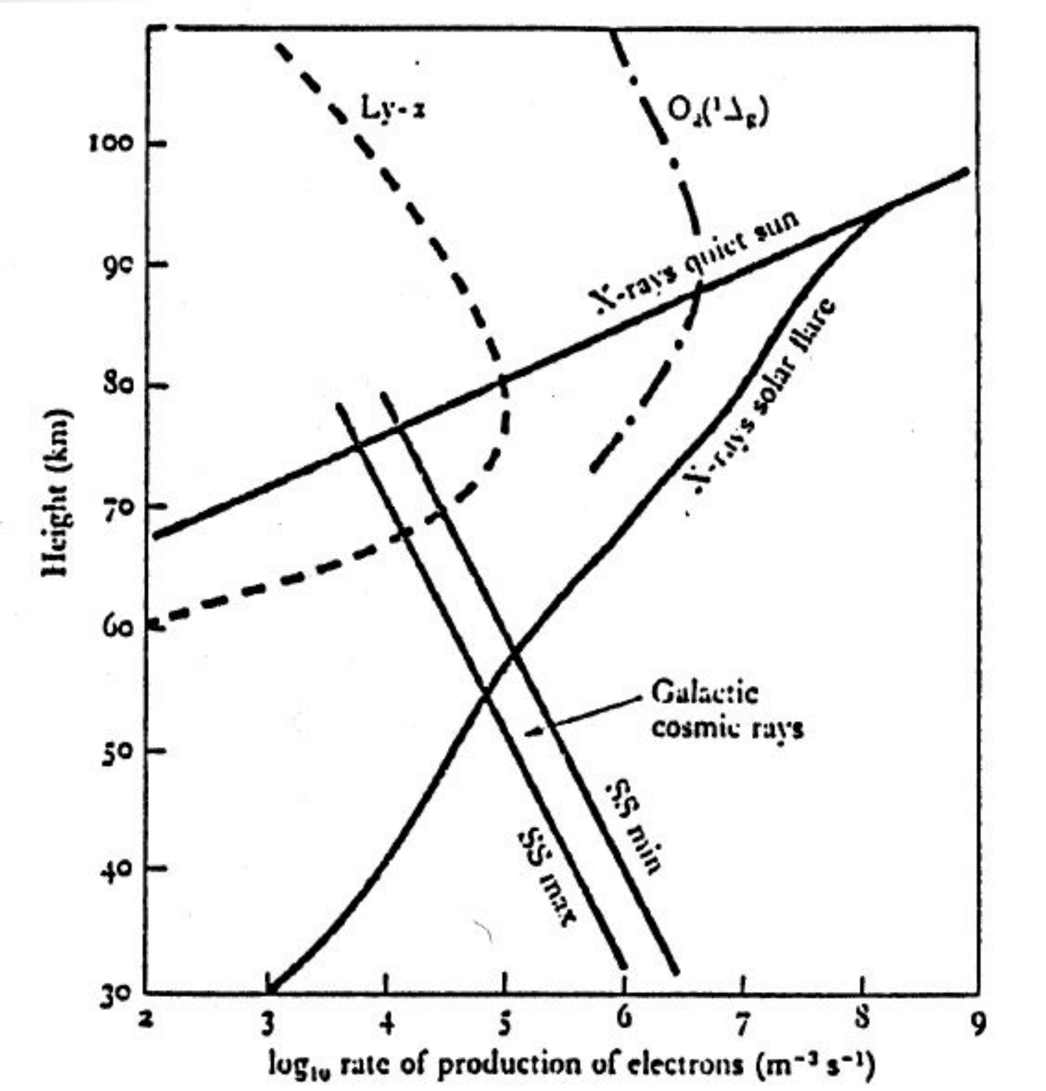
Figure 10.2 Typical composition of the dayside ionosphere at solar minimum. (From *Johnson*.[1])

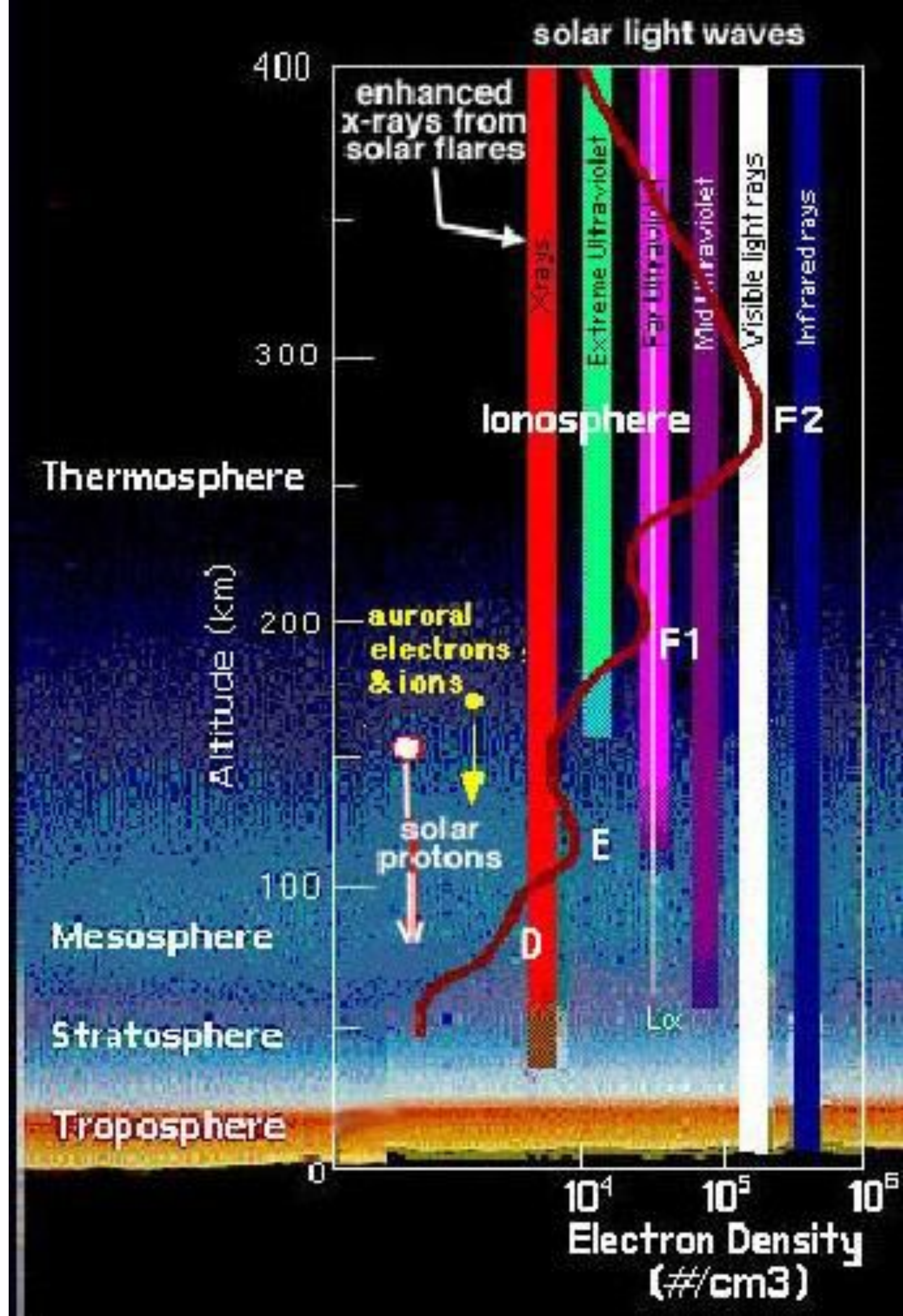
Comparison between neutral and ion density



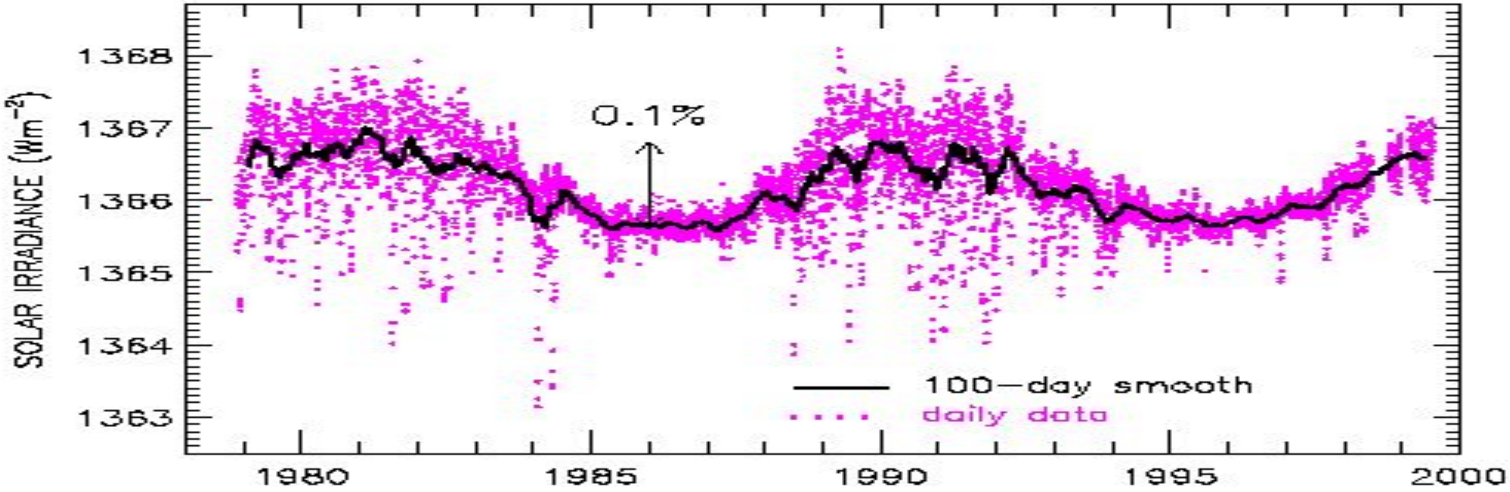
ionosphere

Ionosphere formation

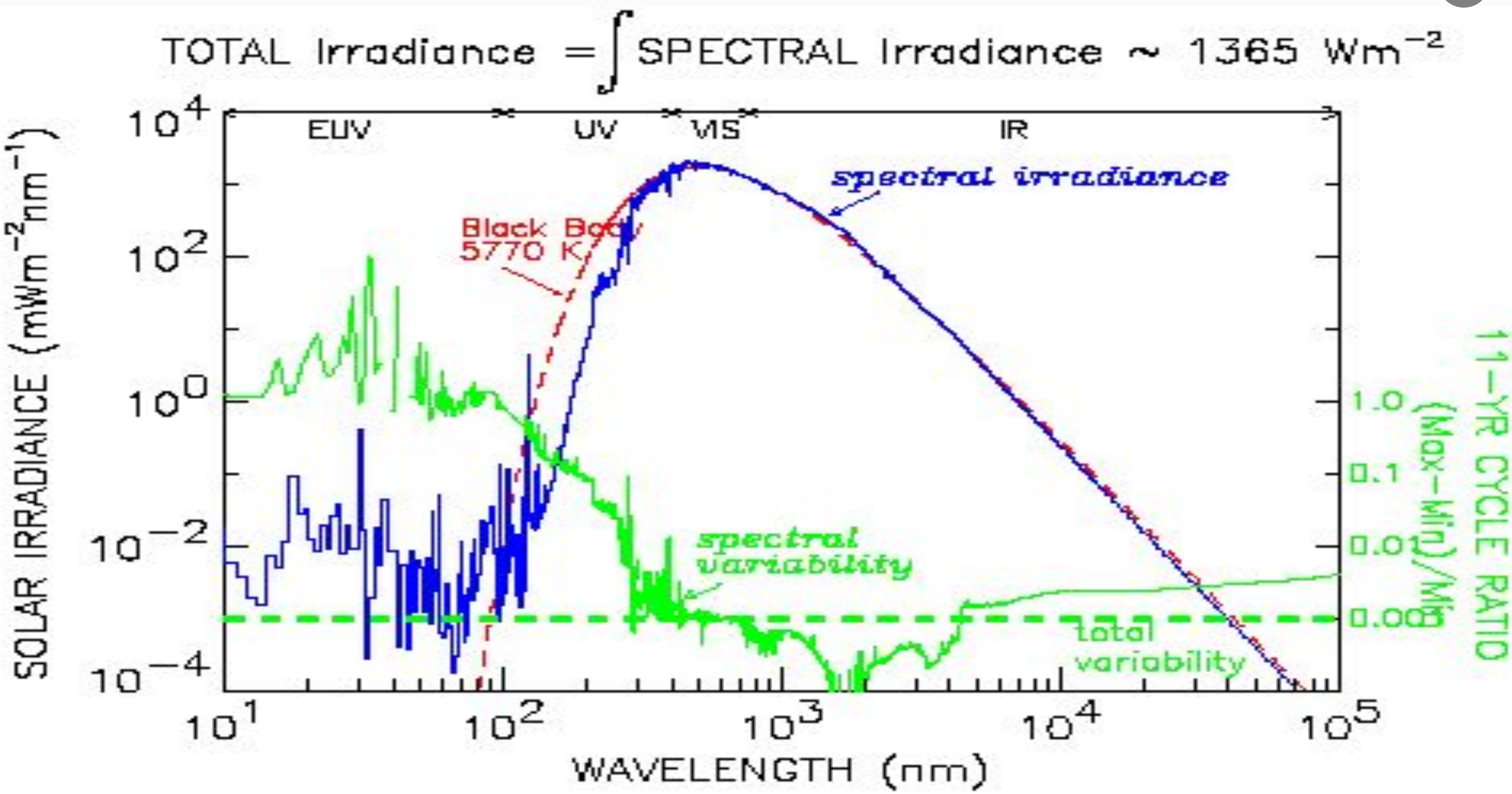




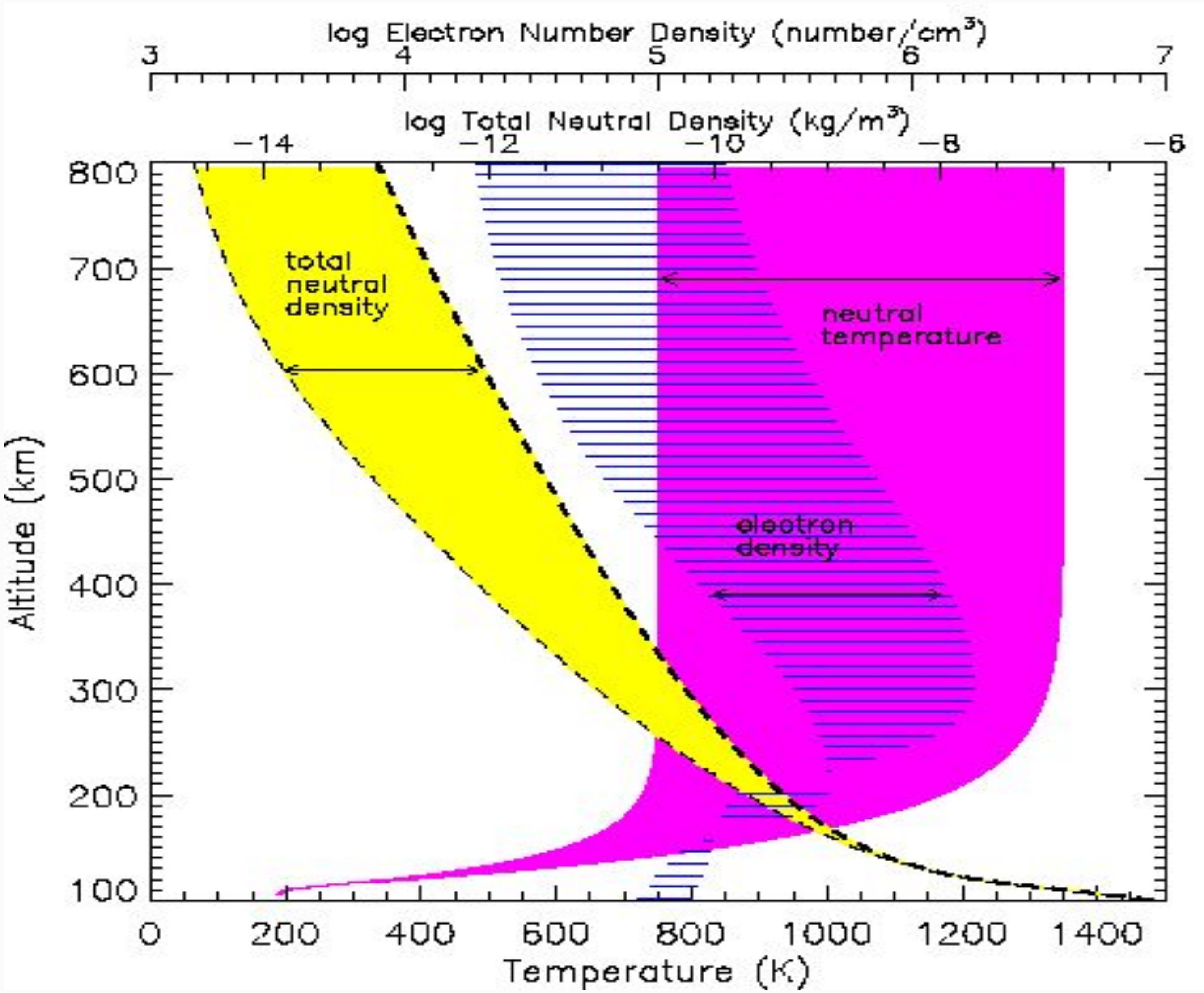
TOTAL IRRADIANCE VARIABILITY



SPECTRUM VARIABILITY



Atmospheric densiy and temperature and solar activity



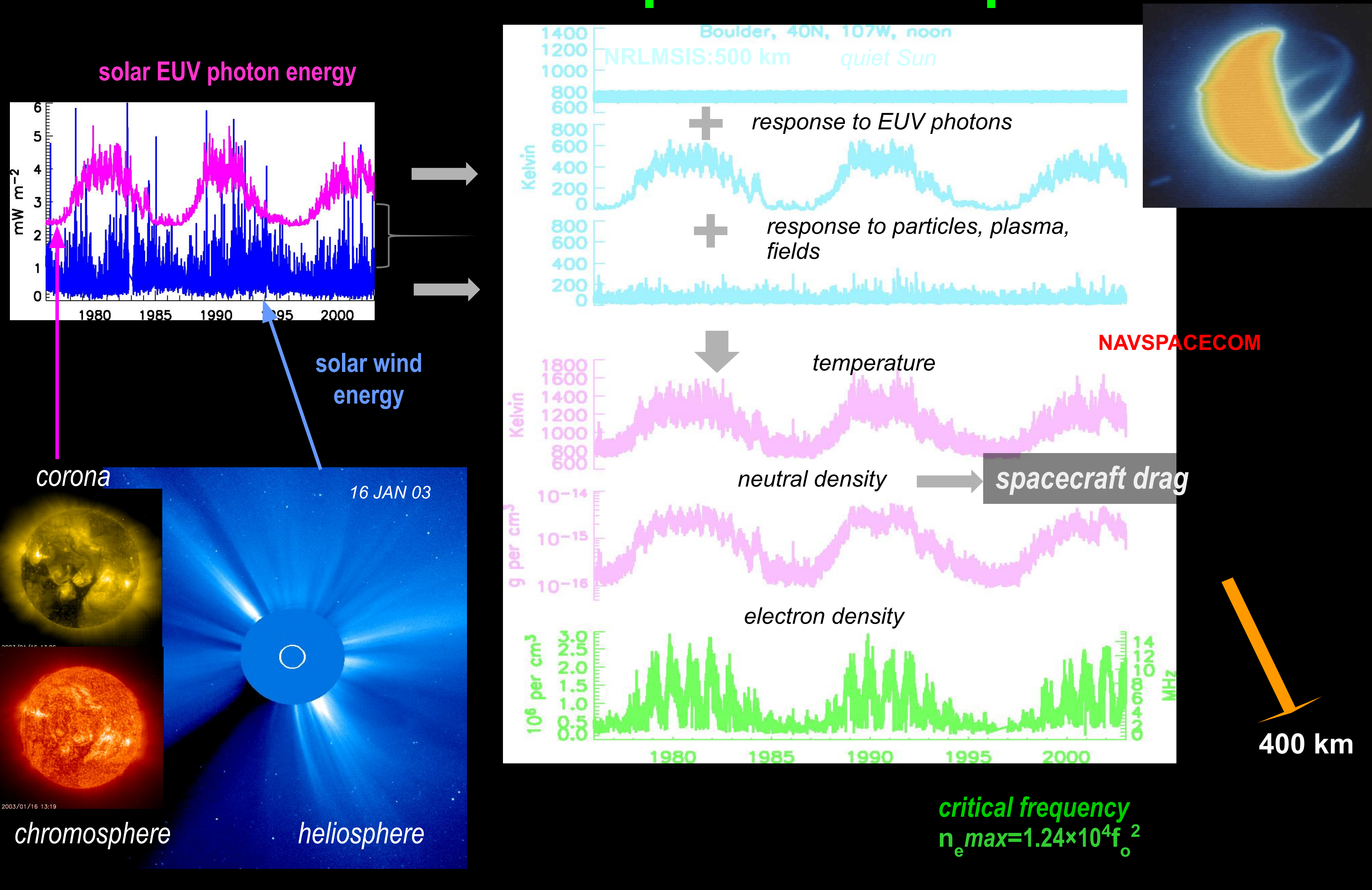
<u>Solar Cycle Changes at 700 km:</u>

Neutral Temperature:
2 times

Neutral Density:
50 times

Electron Density:
10 times

Sun and Thermosphere-Ionosphere



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

D (NO): Ly-α (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. $\sim n_e^2$
  - $A^+ + e^- \longrightarrow A' + \gamma$
  - $BC^+ + e^- \longrightarrow B' + C'$
  - $D + e^- \longrightarrow D^-$
  - $O^+ + O_2 \rightarrow O + O_2^+$; $O_2^+ + e^- \rightarrow O' + O'$

E

D

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):

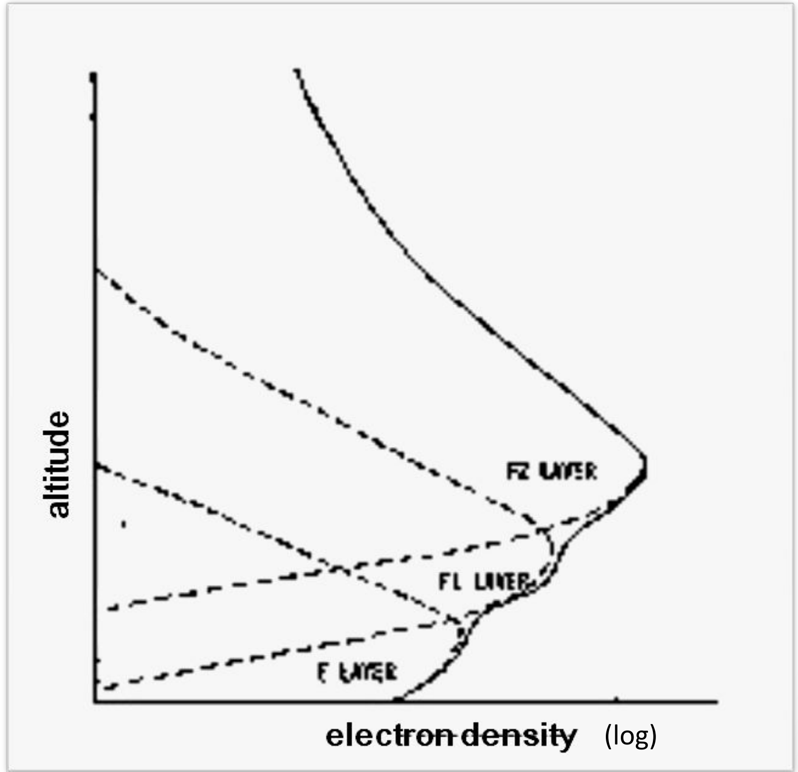
$$\ln(n_{i,1}/n_{i,2}) = -\, m_i g(h_1' - h_2') \,/\, k(T_i+T_e)$$
$$= -\ \ d/D$$

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

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

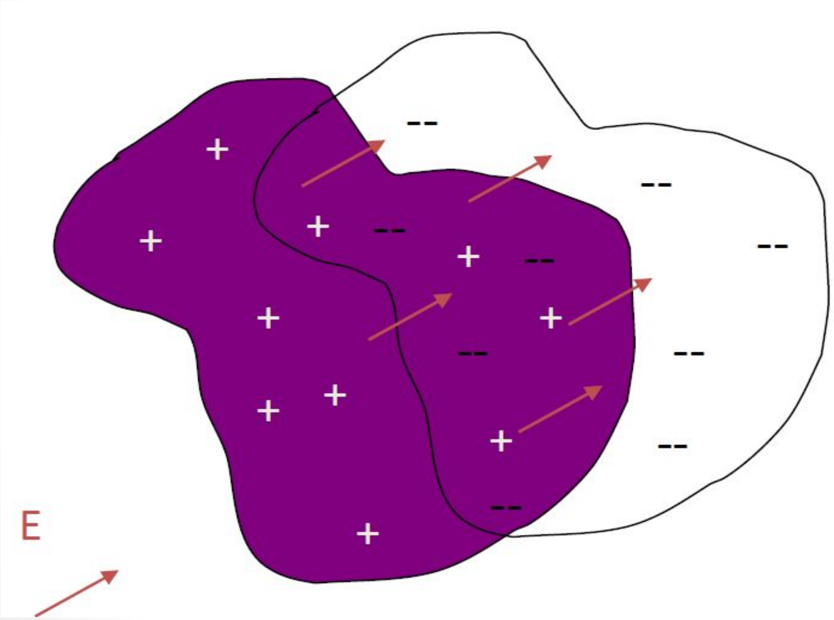
$$\text{Log } n_e = -\text{Log}(e)\ d/D$$
$$d = -D \text{ Log } n_e/\text{Log}(e)$$
$$d = -2.3\ D \text{ Log } n_e$$

$\boxed{O^+ / He^+}$



Ionospheric plasma

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

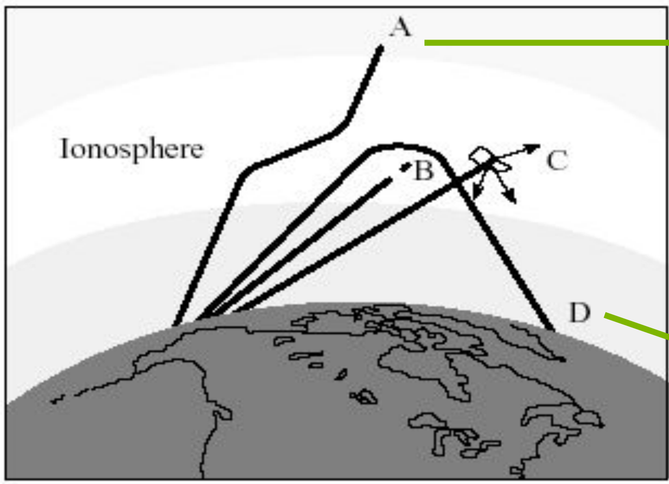


If, by some mechanism, electrons are displaced from ions in a plasma, the resulting separation of charge sets up an electric field which attempts to restore equilibrium. Due to their momentum, the electrons will overshoot the equilibrium point, and accelerate back. **This sets up an oscillation.**

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.

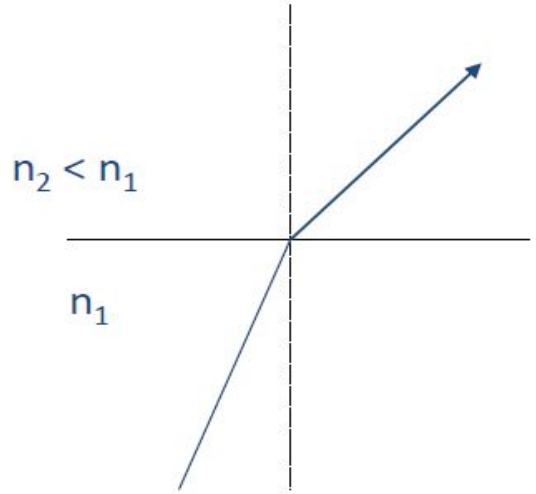
N(m-3)=1/81* f^2 (Hz)

Index of Refraction

*Mathematically, the behavior of a radio wave in a plasma can be viewed in terms of an **index of refraction .***

As a radio wave propagates up into an ionosphere with increasing N_e, n decreases and the ray bends as shown:

Snell's Law



The *index of refraction* for a radio wave in a plasma is given by

$$n = \sqrt{1 - \frac{8.1 \times 10^{-5} N_e}{\nu^2}}$$

Here N_e is the electron density in cm^{-3} and ν is the wave frequency in MHz.

For a given N_e, a high-frequency wave will suffer less refraction than a lower frequency wave, since n is closer to 1 for a high-frequency wave.

The above expression for refractive index becomes imaginary for certain values of N_e / ν, implying ***reflection*** of the radio wave. *For a vertically-propagating wave*, this occurs at the critical value (where n = 0):

$$\nu_c = 9 \times 10^{-3} \sqrt{N_{ec}}$$

Using our previous notations, then, the lowest frequency radio wave capable of penetrating the ionosphere is

$$foF2 = 9 \times 10^{-3} \sqrt{NmF2}$$

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

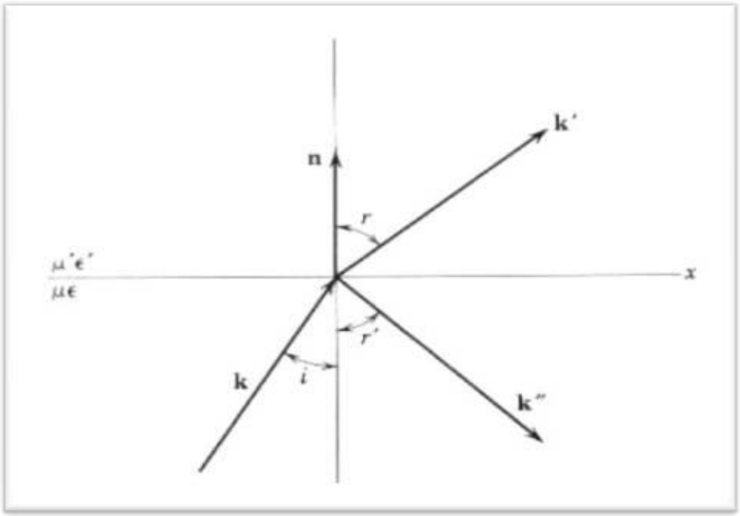
$n = c/u = (1 - 8.06\times10^{-5} n_e / \nu^2)^{1/2}$ refractive index ionized medium

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

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

n_e in cm-3
ν in MHz

Snell's law



$$n = (\mu\varepsilon)^{1/2}$$

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

$$\mu = \text{cost}$$

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

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

Ionogram

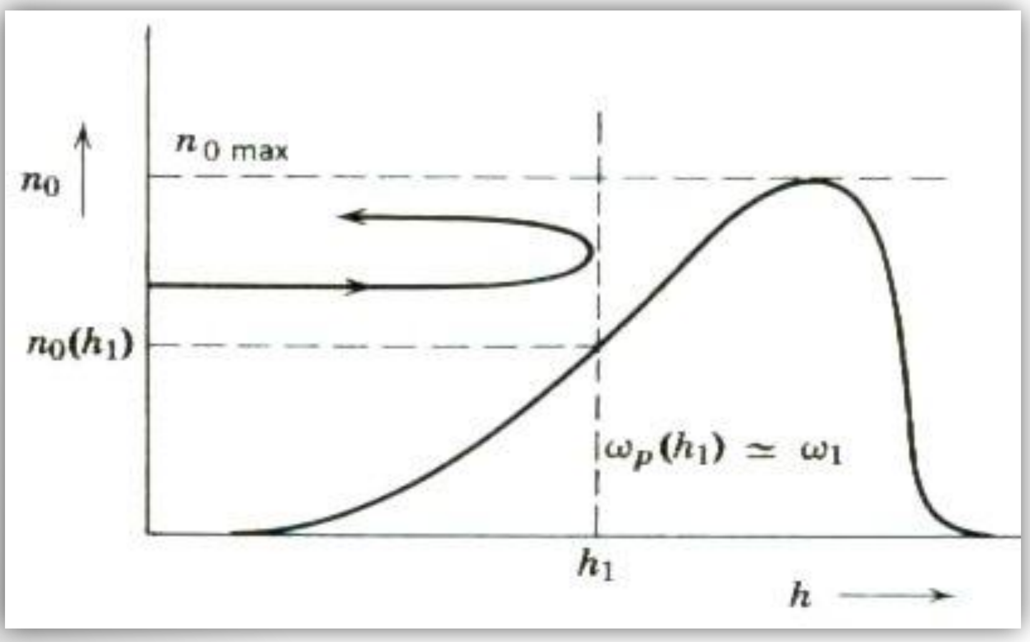
http://ecjones.org/physics.html

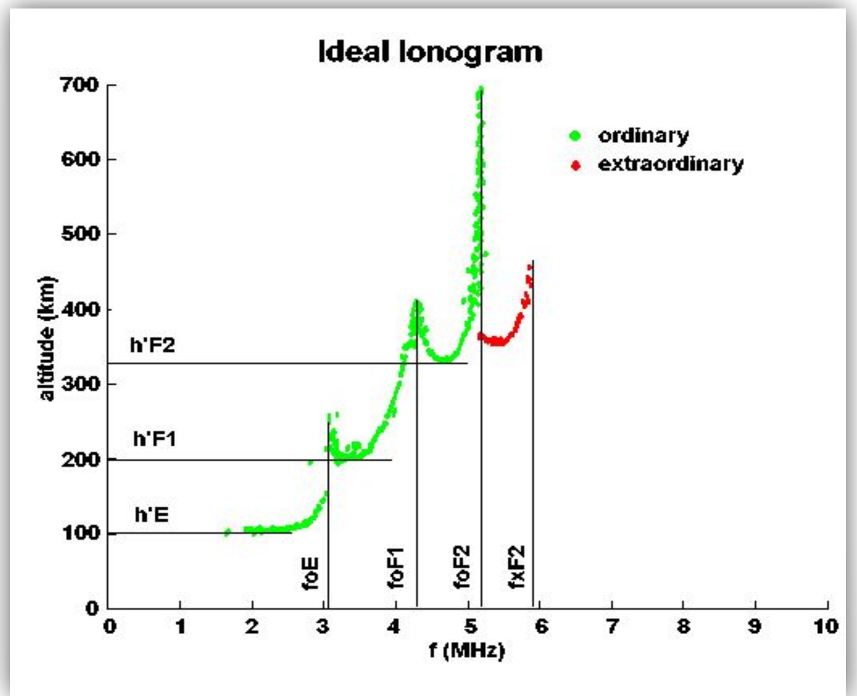
$\varepsilon_\pm = 1 - \omega_p^{\,2} / \omega(\omega \pm \omega_B)$ (+/- circular pol. dx/sx, $\mathbf{E}=(\varepsilon_1 \pm i\varepsilon_2)E$)

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

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

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	3×10^9 - 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 - 0.5μm
Light	$6 \times 10^{14} - 8 \times 10^{14}$Hz	0.5 μm - 0.4μm
Ultra-violet	$8 \times 10^{14} - 10^{17}$Hz	0.4μm - 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 ν^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

Solar effects on radio wave

Radio Noise Storms. Sometimes an active region on the Sun can produce increased noise levels, primarily at frequencies below 400 MHz. This noise may persist for days, occasionally interfering with communication systems using an affected frequency.

Solar Wind Recurrence. The Sun rotates once approximately every 27 days. There is a tendency for long lasting solar wind anomalies, such as those originating from coronal holes, to pass the Earth every 27 days. These solar wind anomalies can cause recurring geomagnetic disturbances.

Solar Radio Bursts. Radio wavelength energy is constantly emitted from the Sun; however, the amount of radio energy may increase significantly during a solar flare. These bursts may interfere with radar, HF (3 – 30 MHz) and VHF (30 – 300 MHz) radio, or satellite communication systems. Radio burst data are also important in helping to predict whether we will experience of the delayed effects of solar particle emissions.

Solar Particle Events and Polar Cap Absorption

Part of the energy released in solar flares are in the form of accelerating particles (mostly proton and electrons) to high energies and released into space.

The major impacts of a solar particle event are spacecraft anomalies (charging, single event upsets, optical sensor disorientation, etc.) and **Polar Cap Absorption** (**PCA**)

PCA events occur when high energy protons spiral along the Earth's magnetic field lines towards the polar ionosphere's D-region (50 – 90 km altitude).

These particles cause significant increased ionization levels, resulting in **severe absorption of HF radio waves** used for communication and some radar system.

This phenomenon, sometimes referred to as "**polar cap blackout**", is often accompanied by widespread **geomagnetic and ionospheric disturbances**.

effect on communication during a PCA event due to changes in the Earth-ionosphere waveguide → Polar airline routes loose ground communications

Exercise

- Assumete (per $|z-z_0| \leq D$)

$$n_e(z) = a\left[1-\left(\frac{z-z_0}{D}\right)^2\right]$$

con:

$a = 10^{12}$ m-3

$z_0 = 300$ km

$D = 200$ km

1. valutare la densita' di distribuzione degli elettroni (grf)
2. calcolate analiticamente l'altezza di riflessione per radio che si propagano verticalmente verso l'alto