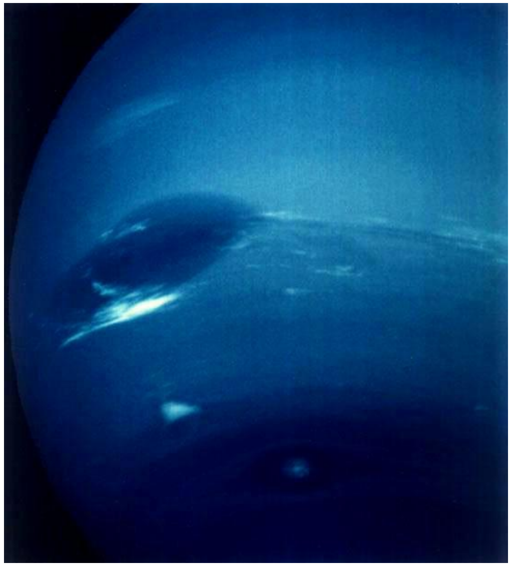
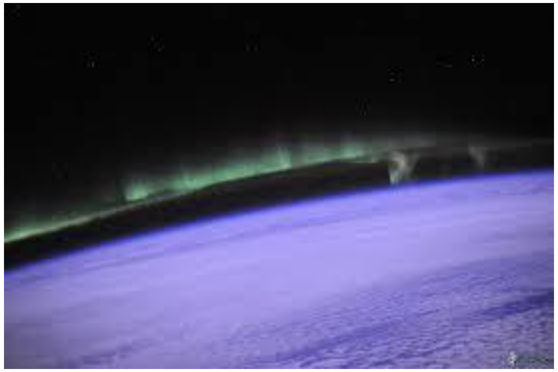
The Atmosphere

Giovanna Jerse





Thickness of the Atmosphere

Approximately 80% of the atmosphere occurs in the lowest 20km above the Earth.

Radius of the Earth is over 6,000 km

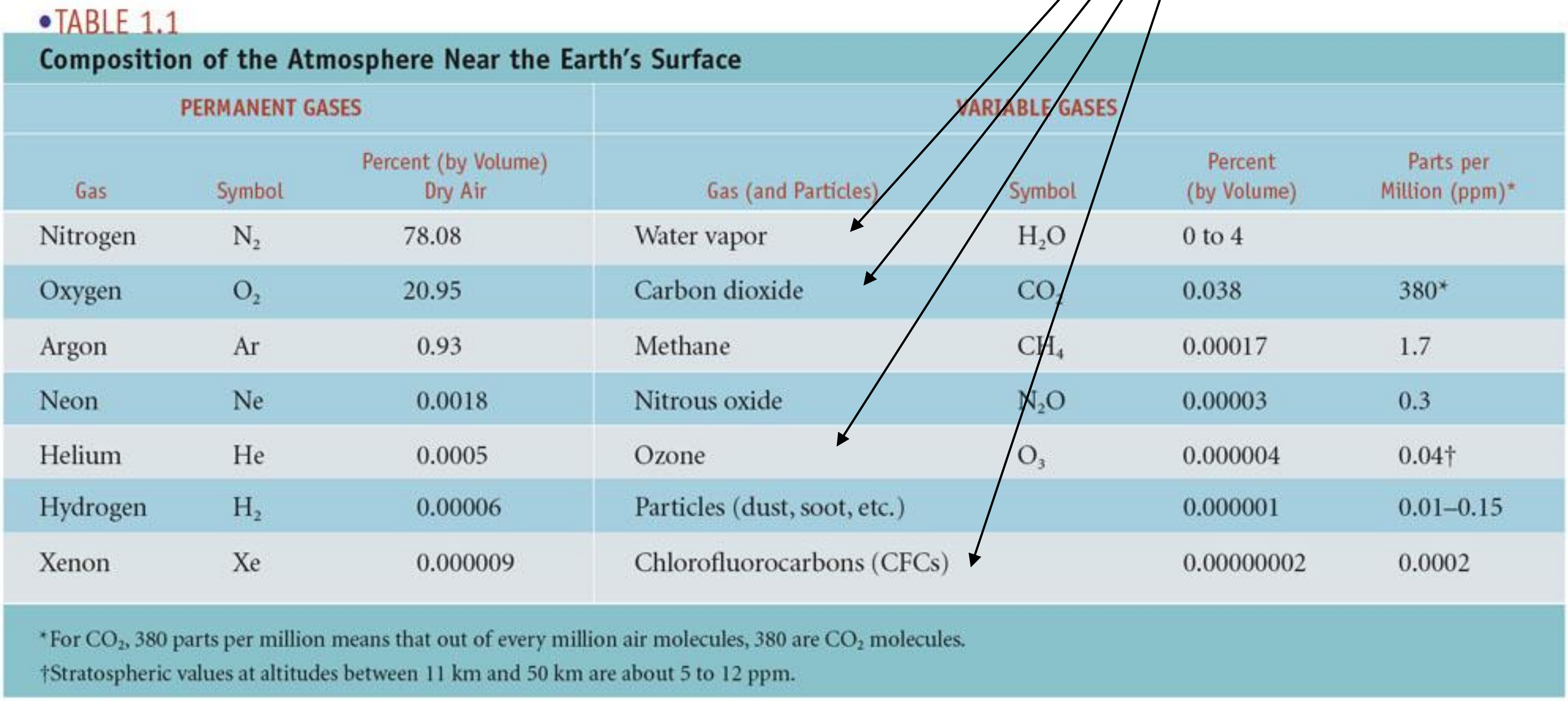
Atmosphere is a thin shell covering the Earth.

But what is the atmosphere?

- Comprised of a 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)

Composition of Earth’s Atmosphere

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

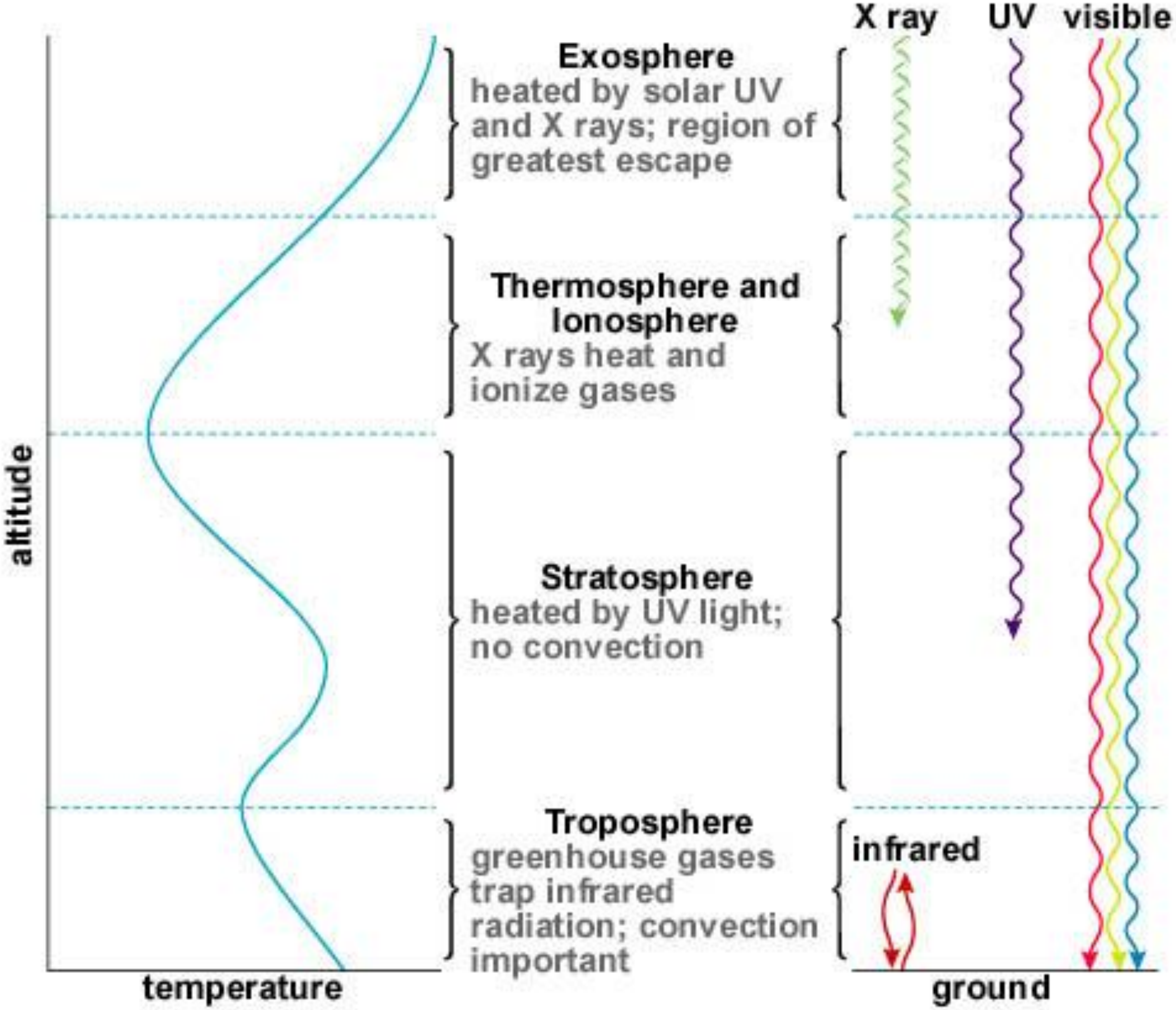
PERMANENT GASES			VARIABLE GASES			
Gas	Symbol	Percent (by Volume) Dry Air	Gas (and Particles)	Symbol	Percent (by Volume)	Parts per Million (ppm)*
Nitrogen	N_2	78.08	Water vapor	H_2O	0 to 4	
Oxygen	O_2	20.95	Carbon dioxide	CO_2	0.038	380*
Argon	Ar	0.93	Methane	CH_4	0.00017	1.7
Neon	Ne	0.0018	Nitrous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

Permanent Gases

- 78% Nitrogen (N_2)
- 21% Oxygen (O_2)
- <1% Argon (Ar)

- Relative percentages of the ***permanent*** gases remain constant up to 80-100km high (~ 60 miles!)
    - This layer is referred to as the Homosphere (implies gases are relatively homogeneous)



Exosphere
heated by solar UV and X rays; region of greatest escape

Thermosphere and Ionosphere
X rays heat and ionize gases

Stratosphere
heated by UV light; no convection

Troposphere
greenhouse gases trap infrared radiation; convection important

2. Atmospheric divisions in terms of temperature structure

The atmosphere of a planet can be divided into different regions. In terms of temperature structure atmosphere is divided into

Troposphere

Lowermost part of the atmosphere where primary heat source is the planetary surface. The heat is convected by turbulent motion leading to a convective or adiabatic distribution.

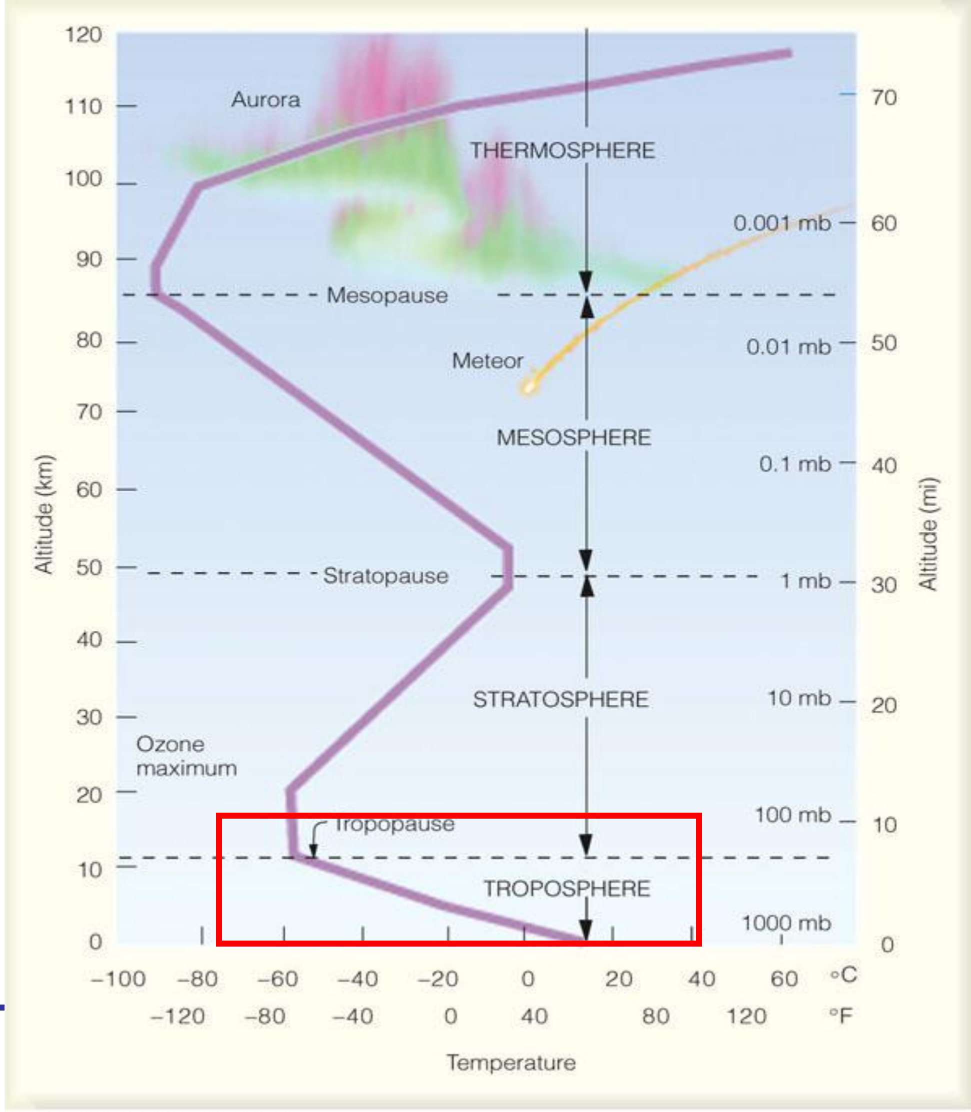
Adiabatic lapse rate is given by $-g/c_p$ where g is the acceleration due to gravity and c_p the specific heat at constant pressure. (depends on planet's acceleration due to gravity and composition).

For earth the theoretical estimate is 10° K/km: observed is 6.5°/km due to presence of water vapour & large-scale circulation.

Tropopause: where the decrease in temperature ceases. For earth tropopause level varies from 18 km at equator to 8 km at poles.

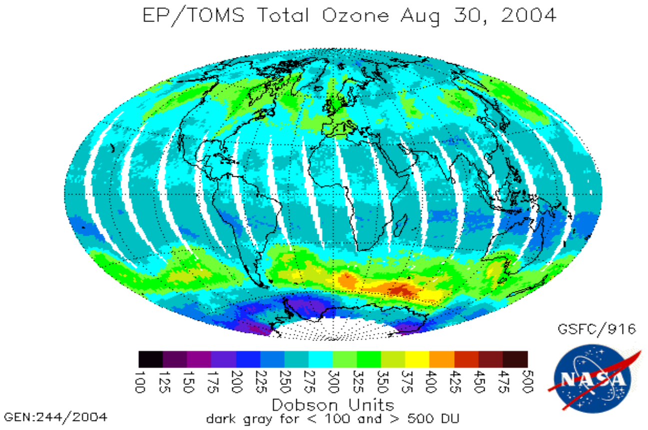
Temperature Layers of the Atmosphere: Troposphere

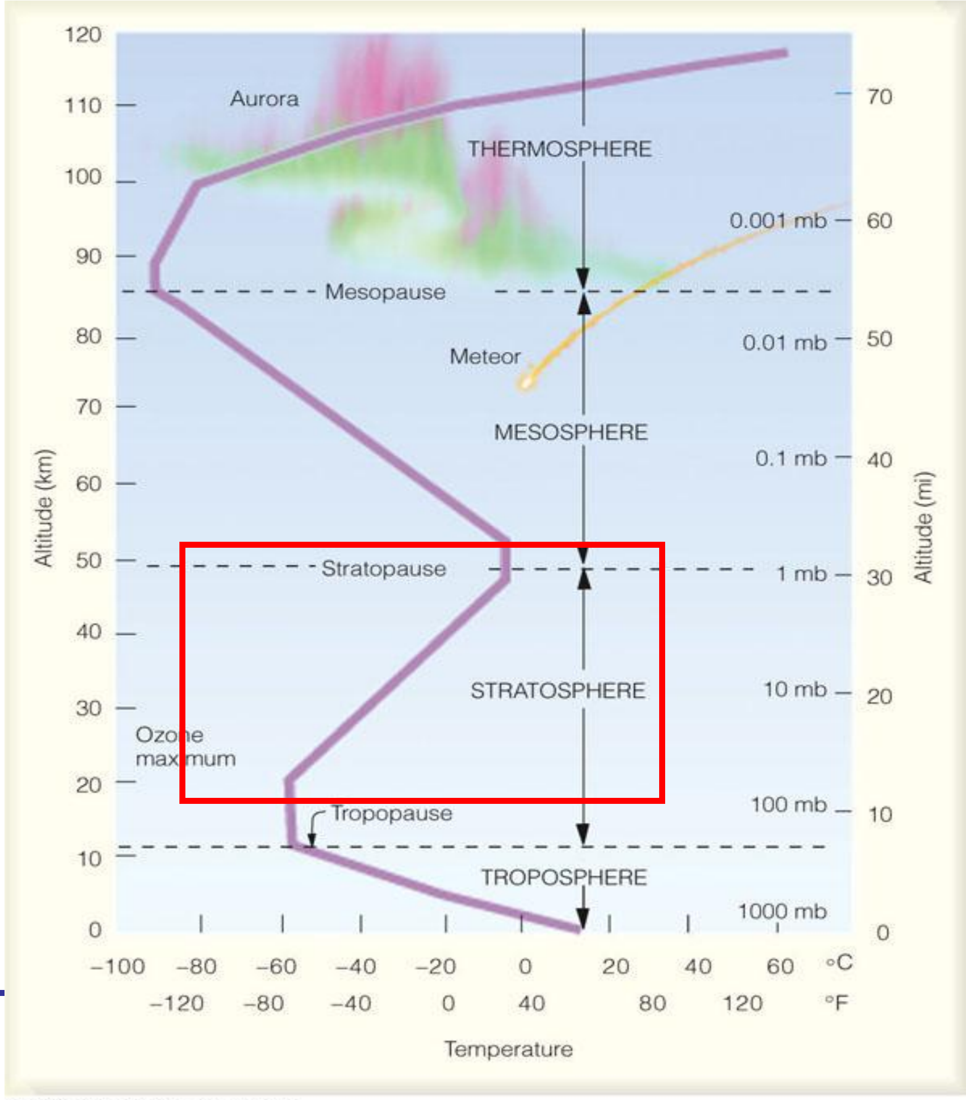
- Lower part of the atmosphere
- Energy source is heating of the earth’s surface by the sun.
- Temperature generally decreases with height.
- Air circulations (weather) take place mainly here.
- Troposphere goes from surface to about 30,000 ft. (10 km).



Temperature Layers of the Atmosphere: Stratosphere

- Sun’s ultraviolet light is absorbed by ozone, heating the air.
- Heating causes increase of temperature with height.
- Boundary between troposphere and stratosphere is the tropopause.
- Stratosphere goes from about 10 to 50 km above the surface.





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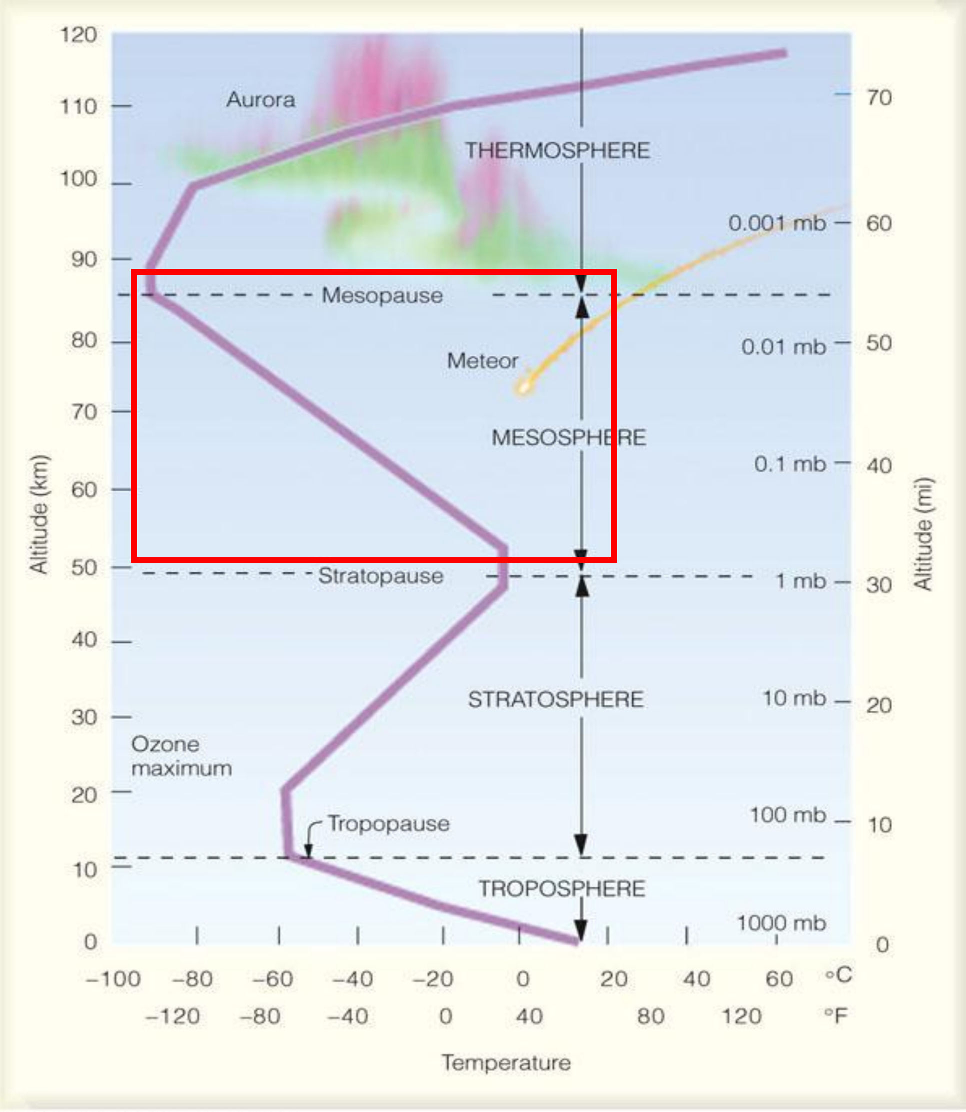
Temperature Layers of the Atmosphere: Mesosphere

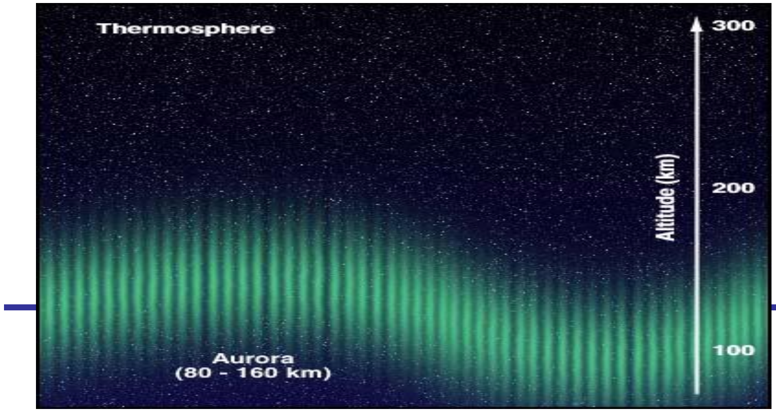
- Above 50 km, very little ozone, so no solar heating
- Air continues to cool with height in mesosphere
- Mesosphere extends from about 50 km to 90 km above the surface

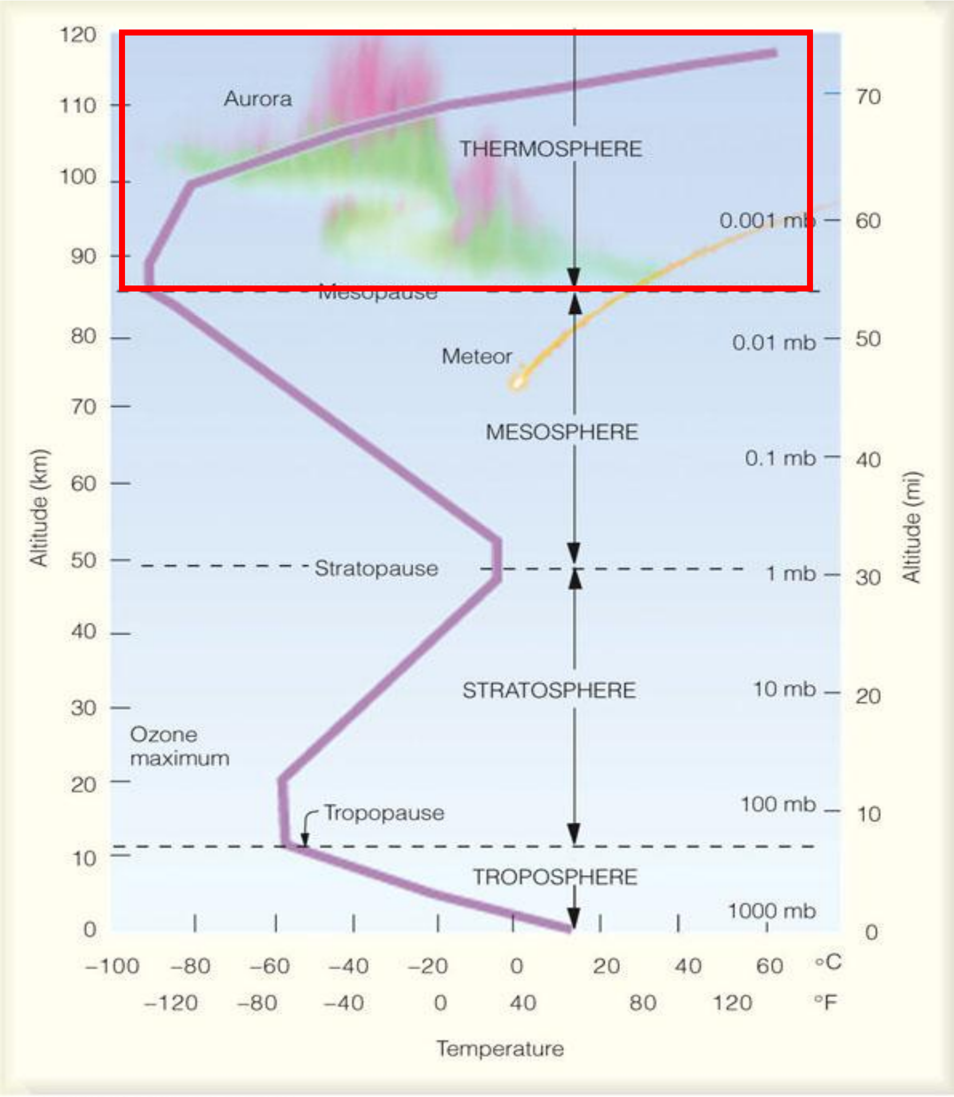

http://www.bath.ac.uk/pr/releases/images/antarctic/noctilucent-clouds.jpg



Temperature Layers of the Atmosphere: Thermosphere

- Above 90 km, residual atmospheric molecules absorb solar wind of nuclear particles, x-rays and gamma rays.
- Absorbed energy causes increase of temperature with height.
- Air molecules are moving fast, but the pressure is very low at these heights.





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2. Atmospheric divisions in terms of temperature structure –3 *Thermosphere*

Above mesopause solar EUV radiation is absorbed and part used in heating so in thermosphere temperature increases with altitude.

In the lower thermosphere convection is principal process of heat transport while in upper thermosphere heat is transported by conduction leading to an isothermal region where temperature is constant above about 500 km (thermopause).

Heating due to the absorption of solar EUV by atmospheric constituents, heat transport due to conduction and convection, loss by IR radiations by constituents govern the energy budget.

Collisions between charged particles and neutrals, Joule heating, atmospheric waves (tides, internal gravity waves), hydromagnetic waves and solar wind are other sources of heating.

Temperatures show diurnal (minimum at 06h, maximum at 17h LT) and solar cycle variations.

2. Atmospheric divisions in terms of temperature structure -4

Exosphere

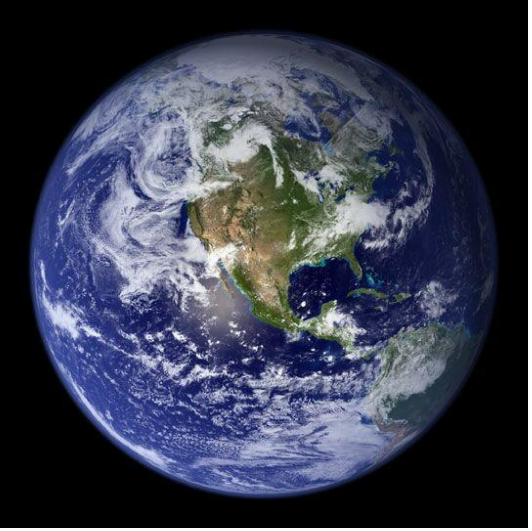
In the region above 500 km (for earth) mean free path becomes large and collisions become negligible so that the light atmospheric constituents whose velocity exceeds the gravitational escape velocity can escape the atmosphere. This region is also called exosphere.

The exobase is also called baropause since the atmosphere below this is also referred to as barosphere, the region where barometric law holds.

In the exosphere velocity distribution becomes non-Maxwellian due to the escape of high velocity particles. For Mars and Venus the exopause is around 200 km (due to lower scale height).

The Main Points

- Planetary atmospheres as a balancing act:
  - Gravity vs. thermal motions of air molecules
  - Heating by Sun vs. heat radiated back into space
  - Weather as a way to equalize pressures at different places on a planet’s surface
- Atmospheres of terrestrial planets are very different now from the way they were born
  - Formation: volcanoes, comets
  - Destruction: escape, incorporation into rocks, oceans
  - Huge changes over a billion years or less
- Prospect of human-induced global warming on Earth is a serious issue. Can be approached scientifically.



Unique Features of Earth's Atmosphere

- Atmospheric composition – high Oxygen content, low Carbon Dioxide content.
- Greenhouse gases contribute to livable surface temperatures
- Most important greenhouse gas is ***water vapor***!
- Without an atmosphere, Earth's surface temp would only be approximately 0°F!
- Water in all three phases: solid, liquid, gas.
- Patchy cloud fields – extensive up and down convective motions in atmosphere.
- Circular motions with storms.

Origin of the atmosphere

a) Earth formed 4.6 billion years ago, *without atmosphere*

b) Outgassing from volcanoes of N_2, CO_2, H_2O, H_2, Cl_2, SO_2, CH_4 , *but not oxygen*

c) Water condensed in oceans, H_2 escaped, acid rain weathered rocks. CO_2 at 100 times present level – *larger greenhouse effect kept the atmosphere warmer and compensated for a 30% weaker Sun*

d) Emergence of life in oceans produced O_2 and sequestered CO_2 in rocks

e) Once O_2 was present O_3 could be formed, *giving UV protection and allowing life to expand its range*

Where do planetary atmospheres come from?

- Three primary sources
  - Primordial (solar nebula)
  - Outgassing (trapped gases)
  - Later delivery (mostly comets)
- How can we distinguish these?
  - Solar nebula composition well known
  - Noble gases are useful because they don't react
  - Isotopic ratios are useful because they may indicate gas loss or source regions (e.g. D/H)
  - ^{40}Ar (^{40}K decay product) is a tracer of outgassing

Atmospheric Compositions

	Earth	Venus	Mars	Titan
Pressure	1 bar	92 bar	0.006 bar	1.5 bar
N_2	77%	3.5%	2.7%	98.4%
O_2	21%	-	-	-
H_2O	1%	0.01%	0.006%	-
Ar	0.93%	0.007%	1.6%	0.004%
CO_2	0.035%	96%	95%	~1ppb
CH_4	1.7ppm	-	?	1.6%
^{40}Ar	6.6×10^{16} kg	1.4×10^{16} kg	4.5×10^{14} kg	3.5×10^{14} kg
H/D	3000	63	1100	3600
$^{14}N/^{15}N$	272	273	170	183

Isotopes are useful for inferring outgassing and atmos. loss

Not primordial!

- Terrestrial planet atmospheres are not primordial (How do we know?)
- Why not?
  - Gas loss (due to impacts, rock reactions or Jeans escape)
  - Chemical processing (e.g. photolysis, rock reactions)
  - Later additions (e.g. comets, asteroids)
- Giant planet atmospheres are *close* to primordial:

	Solar	Jupiter	Saturn	Uranus	Neptune
H_2	84	86.4	97	83	79
He	16	13.6	3	15	18
CH_4	0.07	0.2	0.2	2	3

Values are by number of molecules

Why is the H/He ratio not constant?

Atmospheric Loss

- Atmospheres can lose atoms from stratosphere, especially low-mass ones, because they exceed the escape velocity (Jeans escape)
- Escape velocity $v_e = (2\,g\,R)^{1/2}$ (where's this from?)
- Mean molecular velocity $v_m = (2kT/m)^{1/2}$
- Boltzmann distribution – negligible numbers of atoms with velocities > 3 x v_m
- Molecular hydrogen, 900 K, 3 x v_m= 11.8 km/s
- Jupiter v_e=60 km/s, Earth v_e=11 km/s
- H cannot escape gas giants like Jupiter, but is easily lost from lower-mass bodies like Earth or Mars
- A consequence of Jeans escape is isotopic fractionation – heavier isotopes will be preferentially enriched

Atmospheric Evolution

- Earth atmosphere originally CO_2-rich, oxygen-free
- How do we know?
- CO_2 was progressively transferred into rocks by the Urey reaction (takes place in presence of water):

$$MgSiO_3 + CO_2 \rightarrow MgCO_3 + SiO_2$$

- Rise of oxygen began ~2 Gyr ago (photosynthesis & photodissociation)
- Venus never underwent similar evolution because no free water present (greenhouse effect, too hot)
- Venus and Earth have ~ same *total* CO_2 abundance
- Urey reaction may have occurred on Mars (water present early on), but *very little* carbonate detected

In an atmosphere in equilibrium, pressure gradient balances gravity

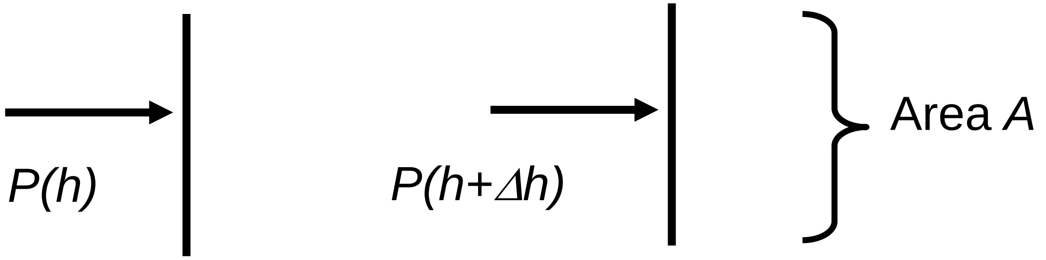
$$\text{Pressure} = \text{Net Force / Area}$$

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

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

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

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



Profile of density with altitude (a calculus-based derivation)

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

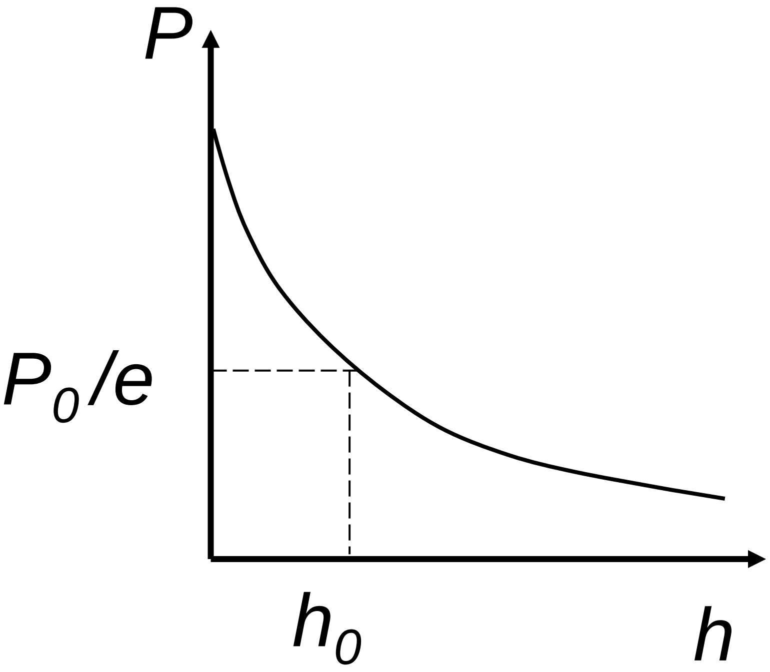
$$\frac{dP}{dh} = \frac{d}{dh}\left(\rho\frac{kT}{m}\right) = -\rho g$$

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

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

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

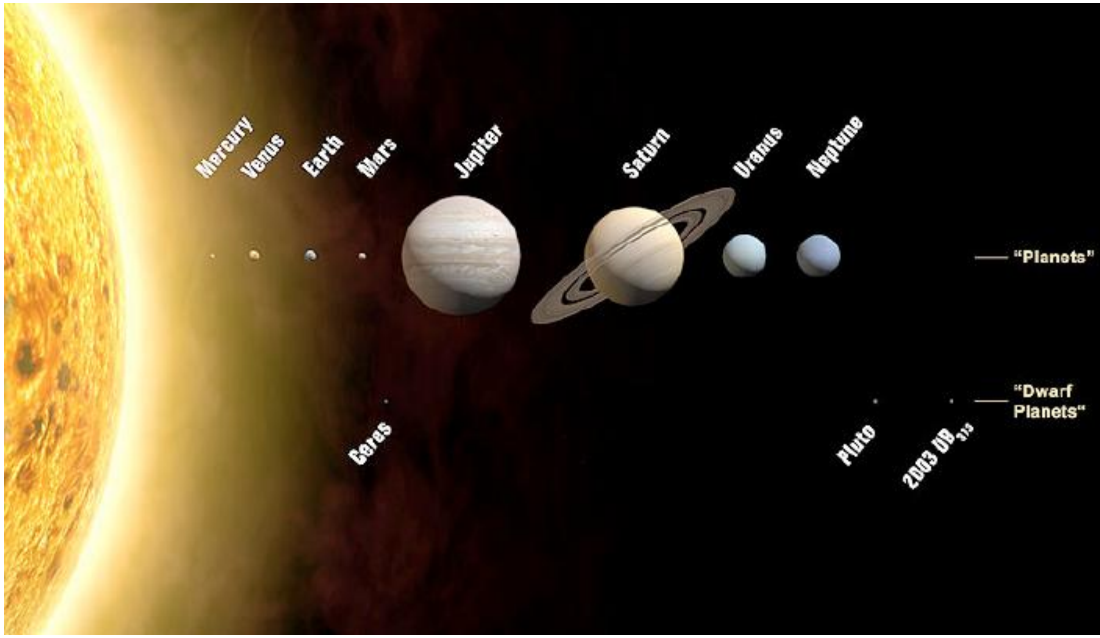
$$\boxed{\text{Solution: } \rho=\rho_0 e^{-(h/h_0)} \text{ where } h_0 = \frac{kT}{mg}}$$



- Pressure, density fall off exponentially with altitude
- Higher temperature $T \Rightarrow$ larger “scale height” h_0
- Stronger gravity $g \Rightarrow$ shorter “scale height” h_0

How big is pressure scale height?

- $h_0 = kT / mg$
  - *height at which pressure has fallen by 1/e = 0.368*
- Earth h_0 = 8 km
  - the thin blue line
- Venus h_0 = 15 km
  - (*g* a bit lower, T higher)
- Mars h_0 = 16 km
  - (both g and T lower)



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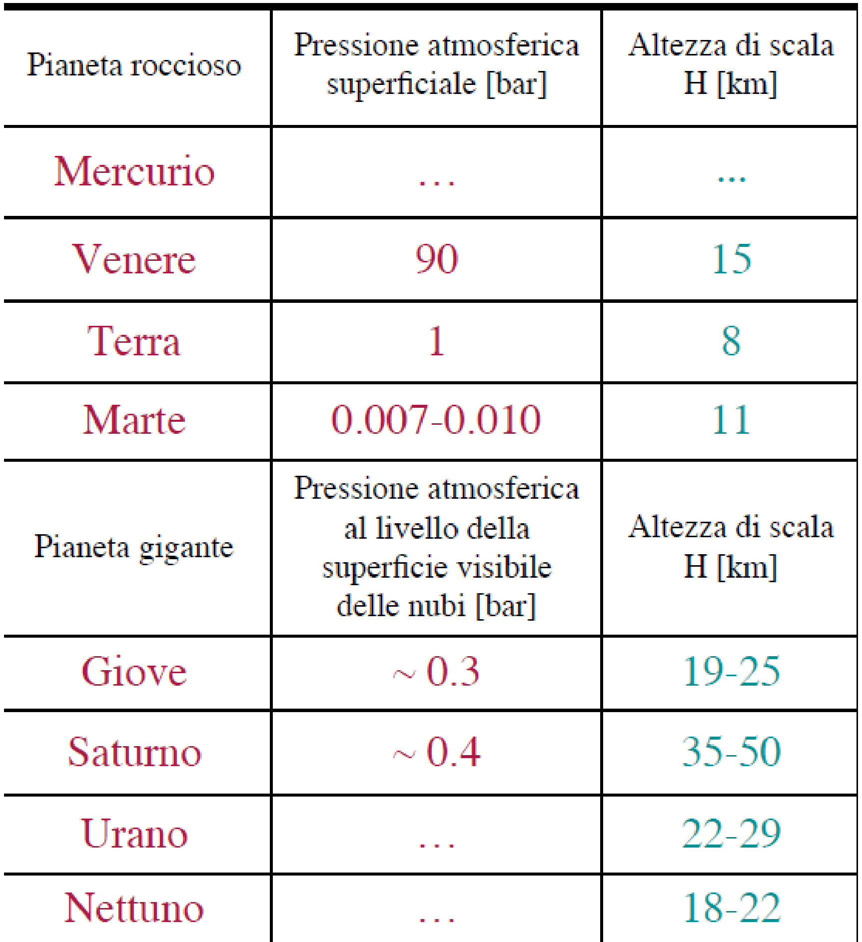


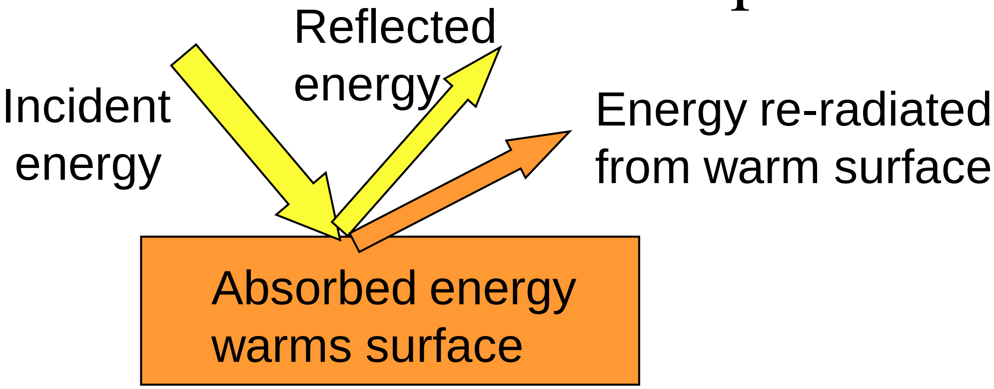
Pianeta roccioso	Pressione atmosferica superficiale [bar]	Altezza di scala H [km]
Mercurio	…	...
Venere	90	15
Terra	1	8
Marte	0.007-0.010	11
Pianeta gigante	Pressione atmosferica al livello della superficie visibile delle nubi [bar]	Altezza di scala H [km]
Giove	~ 0.3	19-25
Saturno	~ 0.4	35-50
Urano	…	22-29
Nettuno	…	18-22

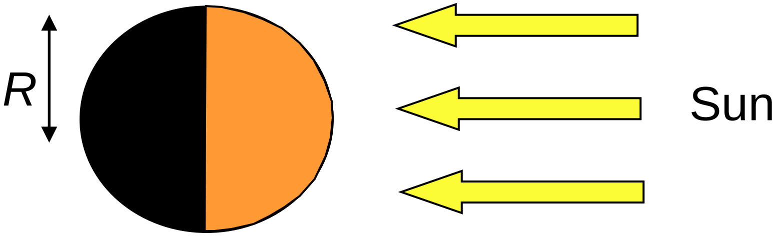
Tabella: Parametri

Pianeta	**Densità g/cm3**	**Temp.Sup K**	**Gravità Terra =1**	**Vel.fuga m/s**	**Composizione atmosferica**
Mercurio	5.42	440	0.37	4.3	Trace?
Venere	5.25	730	0.89	10.4	CO_2 (96%) +N_2 (3.5%) + SO_2 (130 ppm)
Terra	5.51	288	1.0	11.2	N_2 (78%) + O_2 (21%) +Ar (.9%)
Marte	3.96	210	0.39	5.1	CO_2 (95%) + N_2 (2.7%)
Giove	1.35	152	2.65	60.0	H_2 (86%), H_e (14%), CH_4 (0.2%)
Saturno	0.69	143	1.65	36.0	H_2 (97%), H_e (3%), CH_4 (0.2%)
Urano	1.44	68	1.0	22.0	H_2 (83%), H_e (15%), CH_4 (2%)
Nettuno	1.65	53	1.5	22.0	H_2 (79%), H_e (18%), CH_4 (3%)

Surface Temperature (1)

- What determines a planet's surface temperature?





$$E_{in} = (1-A)\pi R^2 F_E \left(\frac{r_E}{r}\right)^2 \qquad E_{rad} = 4\pi R^2 \varepsilon\sigma T^4$$

A is albedo, F_E is solar flux at Earth's surface, r_E is distance of Earth to Sun, r is distance of planet to Sun, ε is emissivity, σ is Stefan's constant ($5.67\text{x}10^{-8}\,\text{Wm}^{-2}\text{K}^{-4}$)

- Balancing energy in and energy out gives:

$$T_{eq} = \left(\left(\frac{r_E}{r}\right)^2 \frac{F_E(1-A)}{4\varepsilon\sigma} \right)^{1/4}$$

Surface Temperature (2)

- Solar constant F_E=1370 Wm^{-2}
- Earth (Bond) albedo A=0.28, ε=1
- Equilibrium temperature = 255 K
- How reasonable is this value?

$$T_{eq} = \left(\left(\frac{r_E}{r} \right)^2 \frac{F_E(1-A)}{4\varepsilon\sigma} \right)^{1/4}$$

σ is Stefan's constant 5.67x10^{-8} in SI units

Body	Mercury	Venus	Earth	Mars
A	0.12	0.75	0.29	0.16
T_{eq}	446	238	255	216
Actual T	100-725	733	288	222

- How to explain the discrepancies?
- Has the Sun's energy stayed constant with time?

Surface temperature (3)

- At distance d from Sun, a planet of radius R receives: $P_{abs} = \frac{L_{sun}}{4\pi d^2} \times \pi R^2 \; W$ where L_{sun} is the solar luminosity in W.

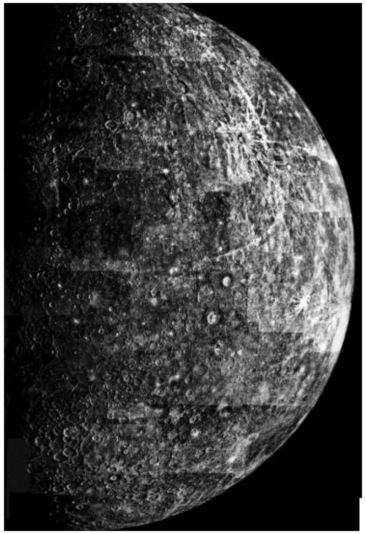
- At 1 AU, Flux $(F) = L_{sun} / 4\pi d^2 = 3.85 \times 10^{26} / 4\pi (1.49 \times 10^{11})^2 = 1370\ W/m^2$.

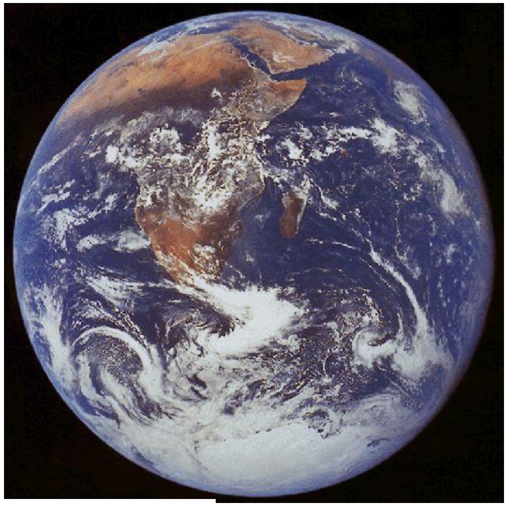
- But, a fraction (A) of power is reflected - A called planetary *albedo* ($0 \leq A \leq 1$).
  - $A = 1$: Total reflection.
  - $A = 0$: Total absorption.

- Fraction ($1 - A$) is absorbed by surface of planet.

- Rocks are poor reflectors and have low albedos, ice is a moderate reflector.

Comparison with terrestrial planets





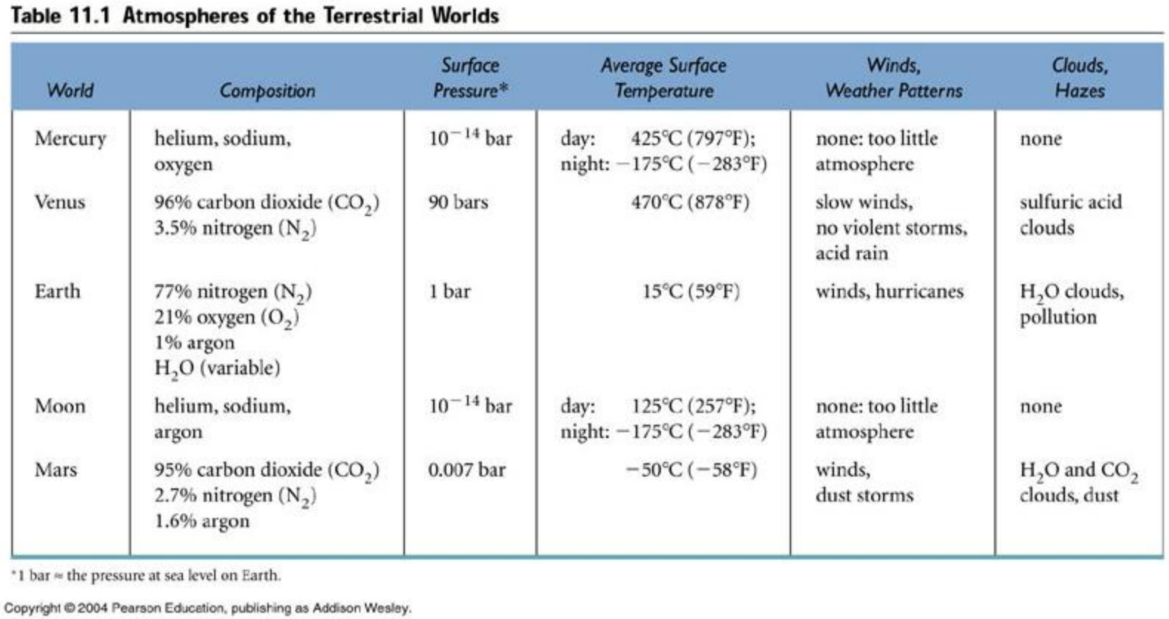


Table 11.1 Atmospheres of the Terrestrial Worlds

World	*Composition*	*Surface Pressure**	*Average Surface Temperature*	*Winds, Weather Patterns*	*Clouds, Hazes*
Mercury	helium, sodium, oxygen	10^{-14} bar	day: 425°C (797°F); night: −175°C (−283°F)	none: too little atmosphere	none
Venus	96% carbon dioxide (CO_2) 3.5% nitrogen (N_2)	90 bars	470°C (878°F)	slow winds, no violent storms, acid rain	sulfuric acid clouds
Earth	77% nitrogen (N_2) 21% oxygen (O_2) 1% argon H_2O (variable)	1 bar	15°C (59°F)	winds, hurricanes	H_2O clouds, pollution
Moon	helium, sodium, argon	10^{-14} bar	day: 125°C (257°F); night: −175°C (−283°F)	none: too little atmosphere	none
Mars	95% carbon dioxide (CO_2) 2.7% nitrogen (N_2) 1.6% argon	0.007 bar	−50°C (−58°F)	winds, dust storms	H_2O and CO_2 clouds, dust

*1 bar ≈ the pressure at sea level on Earth.

Comparison with Venus

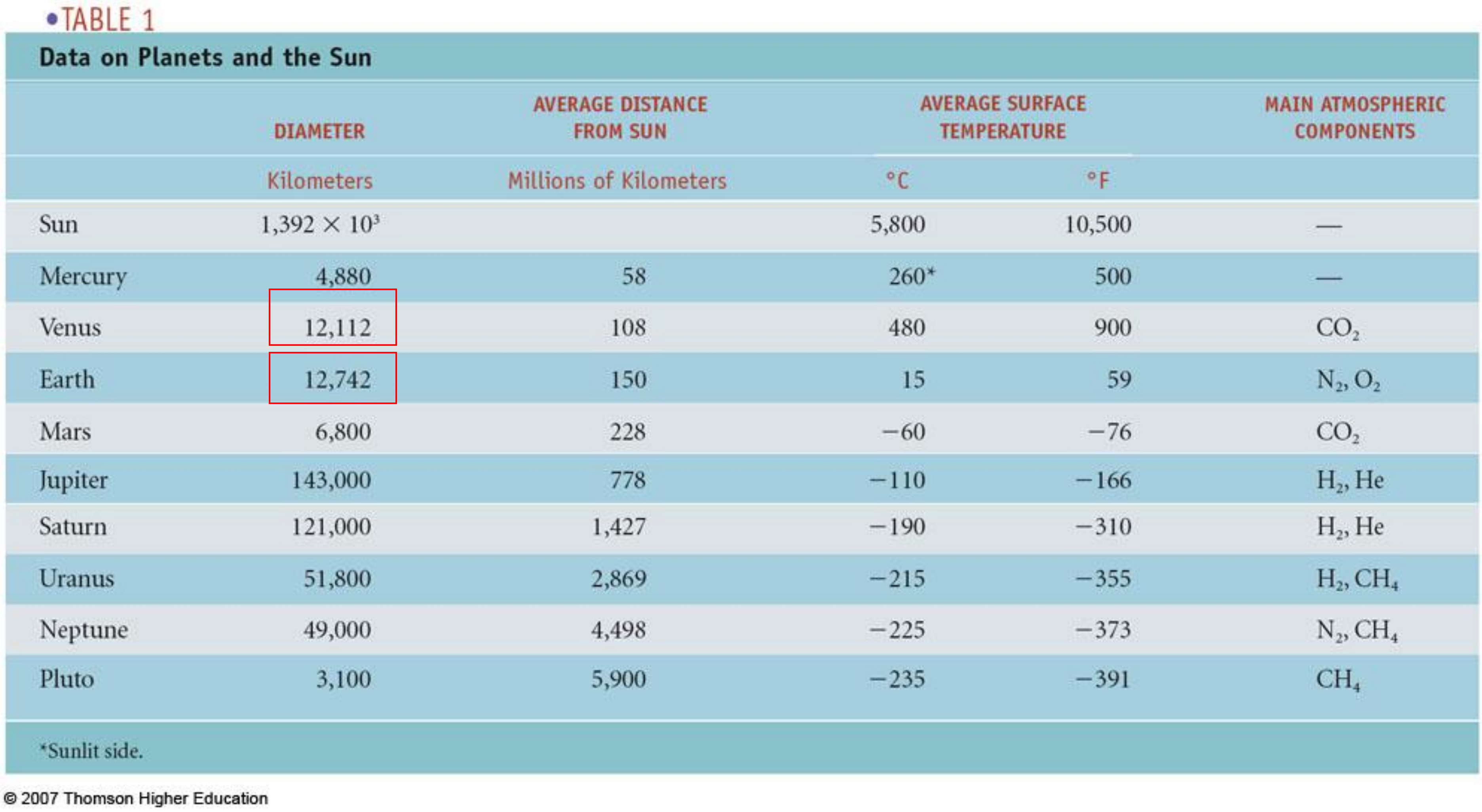
Composition of Venus Atmosphere: 96% $CO_{2,}$ 3% N_2 (compare to Earth—.04% CO_2, 78% N_2)

Pressure at surface: 90,000 mbar (by comparison, Earth's mean sea-level pressure is approximately 1,013 mbar —Venus' surface pressure is 90x greater!)

Temperature at surface: ~ 900°F (by comparison, Earth's mean sfc temperature is about 59°F)

Extreme atmospheric pressures on Venus due large amount of gaseous CO_2.

No mechanisms to remove CO_2 from atmosphere (e.g., photosynthesis, dissolution in water).



•TABLE 1

Data on Planets and the Sun

	DIAMETER	AVERAGE DISTANCE FROM SUN	AVERAGE SURFACE TEMPERATURE		MAIN ATMOSPHERIC COMPONENTS
	Kilometers	Millions of Kilometers	°C	°F	
Sun	1,392 × 10^3		5,800	10,500	—
Mercury	4,880	58	260*	500	—
Venus	12,112	108	480	900	CO_2
Earth	12,742	150	15	59	N_2, O_2
Mars	6,800	228	−60	−76	CO_2
Jupiter	143,000	778	−110	−166	H_2, He
Saturn	121,000	1,427	−190	−310	H_2, He
Uranus	51,800	2,869	−215	−355	H_2, CH_4
Neptune	49,000	4,498	−225	−373	N_2, CH_4
Pluto	3,100	5,900	−235	−391	CH_4

*Sunlit side.

Earth and Venus nearly same size – velocity required to escape gravitational pull similar for both.

Why the drastic difference?


Mariner 10 Image of Venus

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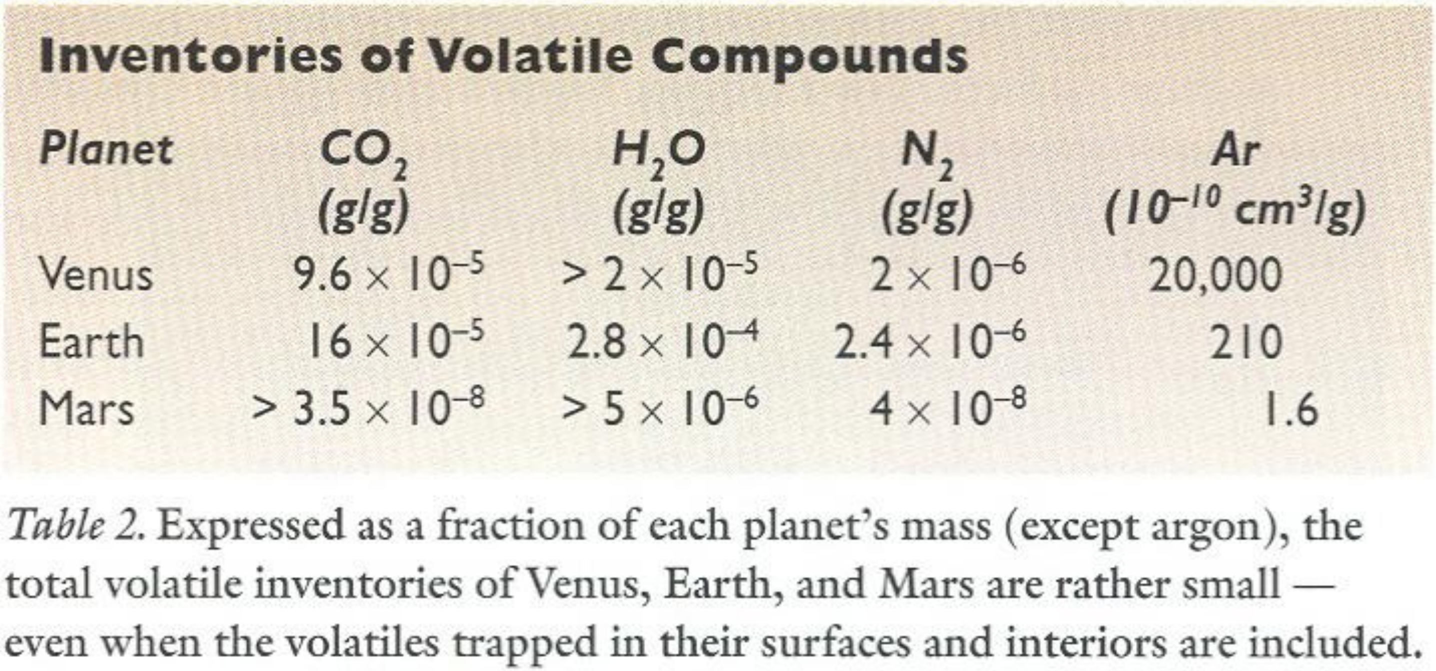
Venus is closer to Sun

Warmer temperatures prevented liquid water from forming.

With no liquid water, no means to dissolve the carbon dioxide.

Result is a rich carbon dioxide atmosphere.

Earth and Venus CO_2 and N_2



Inventories of Volatile Compounds

Planet	CO_2 (g/g)	H_2O (g/g)	N_2 (g/g)	Ar (10^{-10} cm^3/g)
Venus	9.6×10^{-5}	$> 2 \times 10^{-5}$	2×10^{-6}	20,000
Earth	16×10^{-5}	2.8×10^{-4}	2.4×10^{-6}	210
Mars	$> 3.5 \times 10^{-8}$	$> 5 \times 10^{-6}$	4×10^{-8}	1.6

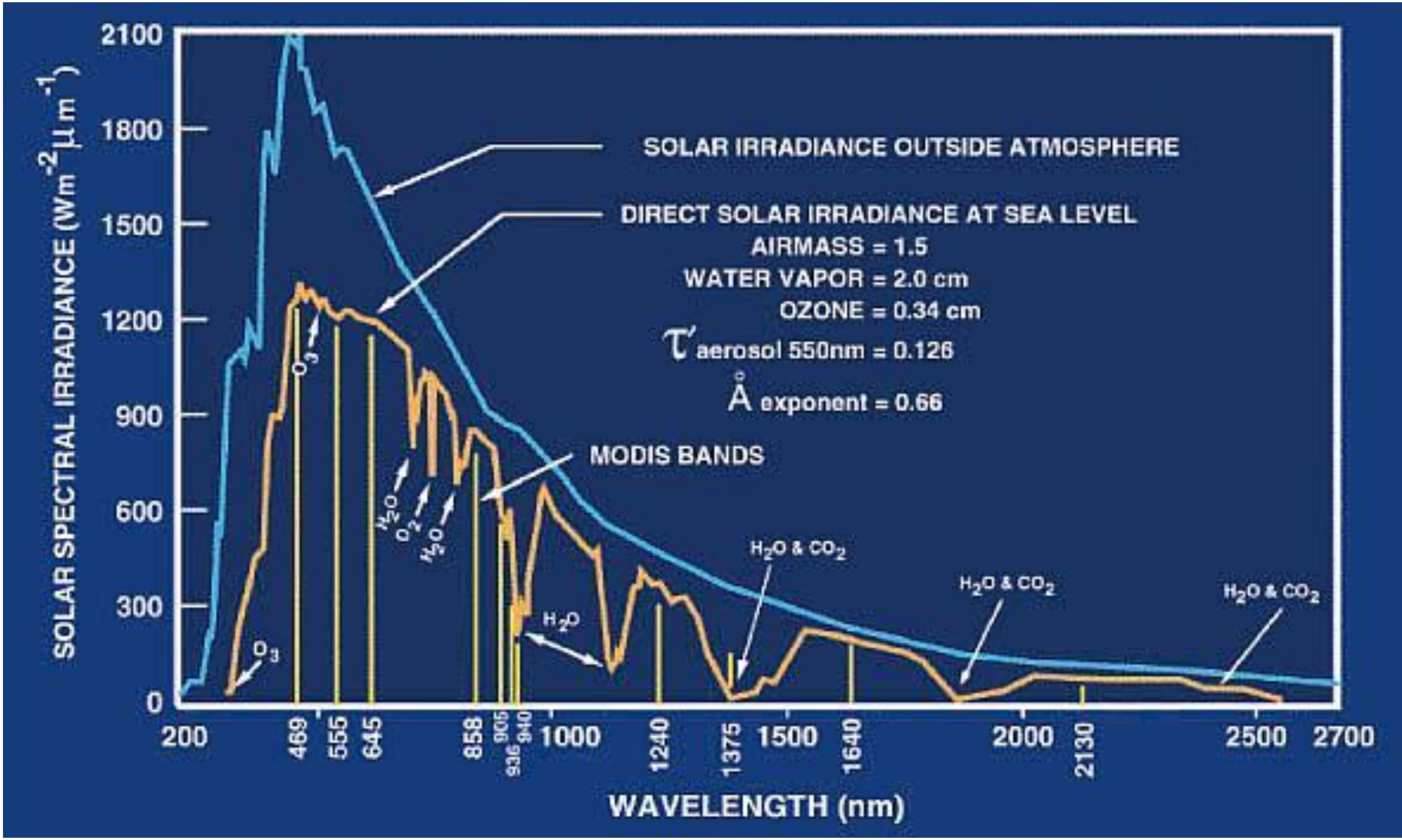
Table 2. Expressed as a fraction of each planet's mass (except argon), the total volatile inventories of Venus, Earth, and Mars are rather small — even when the volatiles trapped in their surfaces and interiors are included.

- Earth actually has *more* CO_2 than Venus (as fraction of total planet m
- Earth and Venus have similar amounts of N_2.
- CO_2 is 96% of Venus atmosphere and only .04% of Earth's.
- Venus has CO_2 in *atmosphere*, while Earth has CO_2 in *limestone*.

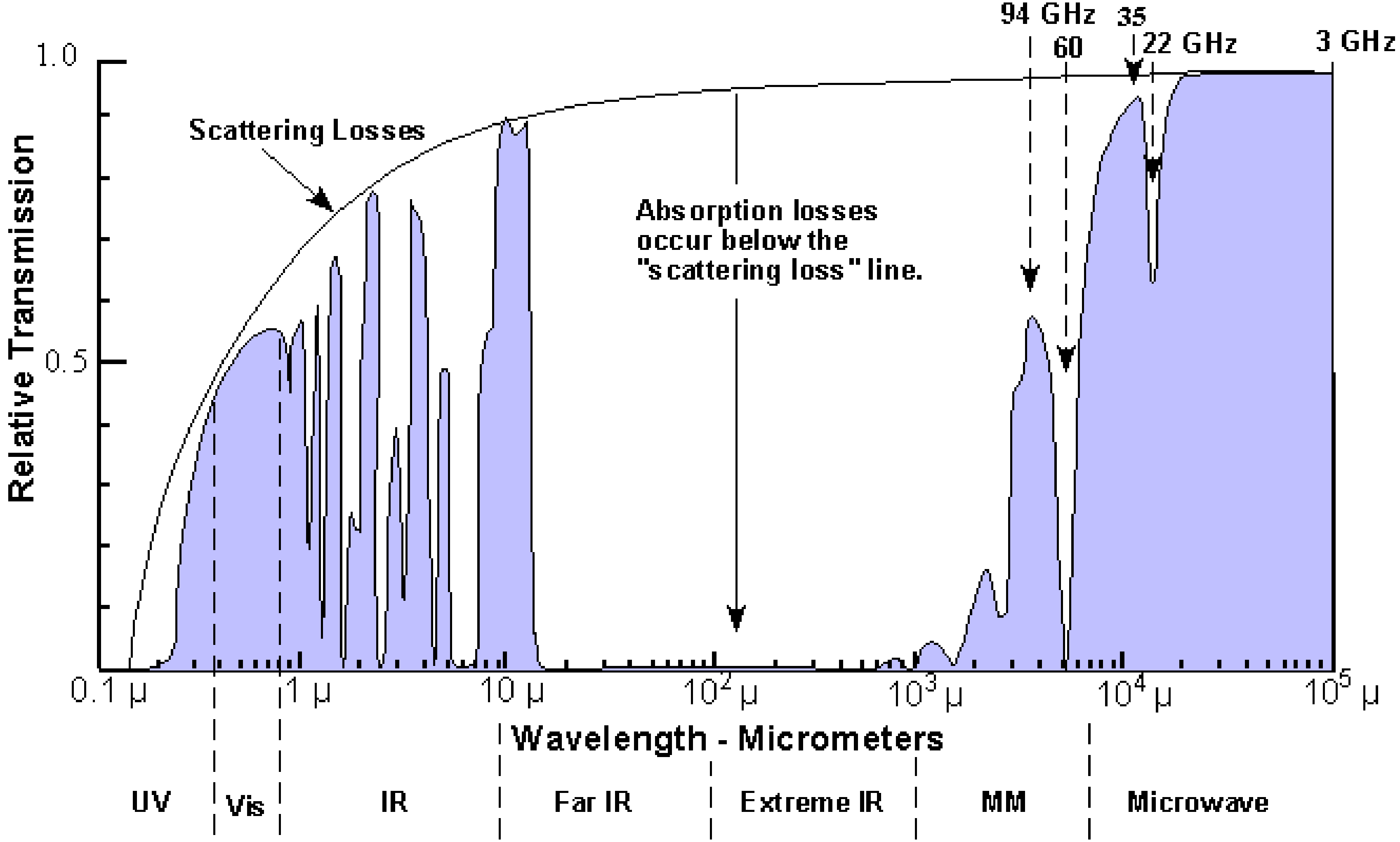
Table 10.2 The Greenhouse Effect on the Terrestrial Worlds

World	*Average Distance from Sun (AU)*	*Reflectivity*	*"No Greenhouse" Average Surface Temperature**	*Actual Average Surface Temperature*	*Greenhouse Warming (actual temperature minus "no greenhouse" temperature)*
Mercury	0.387	12%	163°C	425°C (day), −175°C (night)	—
Venus	0.723	75%	−40°C	470°C	510°C
Earth	1.00	29%	−16°C	15°C	31°C
Moon	1.00	12%	−2°C	125°C (day), −175°C (night)	—
Mars	1.524	16%	−56°C	−50°C	6°C

* The "no greenhouse" temperature is calculated by assuming no change to the atmosphere other than lack of greenhouse warming. Thus, for example, Venus ends up with a lower "no greenhouse" temperature than Earth even though it is closer to the Sun, because the high reflectivity of its bright clouds means that it absorbs less sunlight than Earth.


SOLAR SPECTRAL IRRADIANCE ($Wm^{-2}\mu m^{-1}$)
2100
1800
1500
1200
900
600
300
0
SOLAR IRRADIANCE OUTSIDE ATMOSPHERE
DIRECT SOLAR IRRADIANCE AT SEA LEVEL
AIRMASS = 1.5
WATER VAPOR = 2.0 cm
OZONE = 0.34 cm
$\tau'_{\text{aerosol 550nm}}$ = 0.126
$\mathring{A}$ exponent = 0.66
MODIS BANDS
O_3
O_3
H_2O
O_2
H_2O
H_2O
H_2O & CO_2
H_2O & CO_2
H_2O & CO_2
200
469
555
645
858
905
936
940
1000
1240
1375
1500
1640
2000
2130
2500
2700
WAVELENGTH (nm)

ATTENUATION OF EM WAVES BY THE ATMOSPHERE



Atmospheric retention (1)

- Energy of a molecule in atmosphere can be written:

$$E_{total} = E_k + E_p = 1/2mv^2 - \frac{GMm}{r} = 0$$

- A particle will escape from planet if has enough KE. Escape speed $v = v_{esc}$, needed to escape from $r = R$ is therefore:

$$\boxed{v_{esc} = \sqrt{\frac{2GM}{R}}}$$

- From kinetic theory, $1/2mv_{therm}^2 = 3/2kT$ therefore,

$$\boxed{v_{therm} = \sqrt{\frac{3kT}{m}}}$$

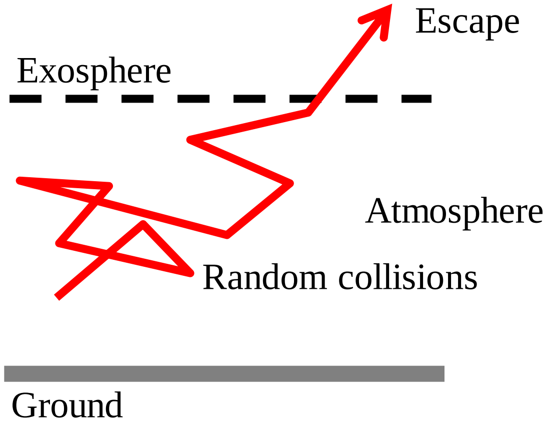
- Lightest particles (H and He) have highest speeds and escape preferentially if T is large enough for particles to have $v_{therm} > v_{esc}$.

Atmospheric retention (2)

- A planet will retain its atmosphere if $v_{therm} < v_{esc}$
- The escape condition occurs when

$$\sqrt{\frac{3kT}{m}} = \sqrt{\frac{2GM}{R}}$$

$$\boxed{=> T_{esc} = \frac{2GMm}{3kR}}$$



- The region where this condition is met is called the *exosphere.*
- If surface temperature is large, planet will loose atmosphere. Also, small planets find it difficult to hold onto atmospheres.
- For a given planet or satellite of mass M and radius R the atmospheric retention condition is

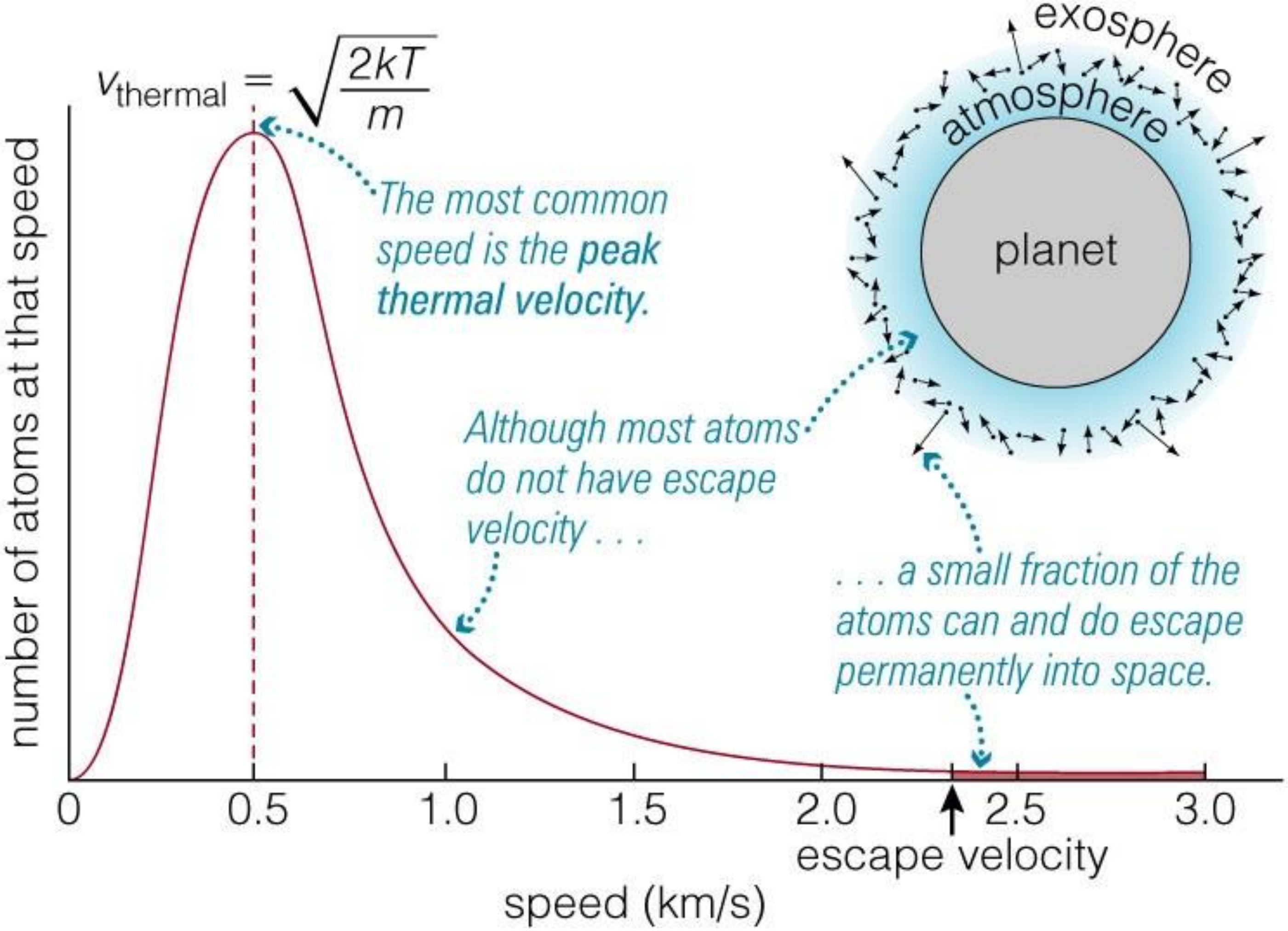
$$T_{atm} < T_{esc}$$

Atmospheric retention (3)

- 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.



$$v_{\text{thermal}} = \sqrt{\frac{2kT}{m}}$$

The most common speed is the ***peak thermal velocity.***

Although most atoms do not have escape velocity . . .

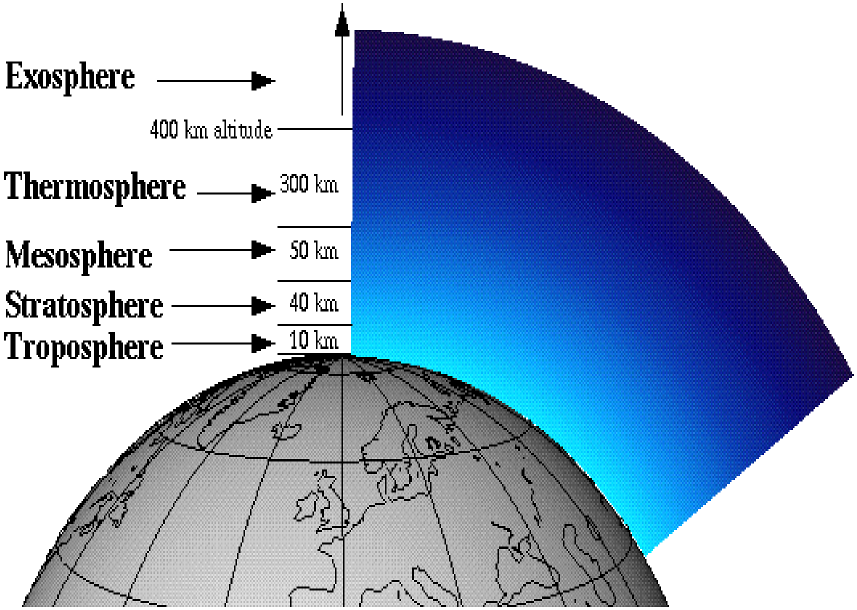
. . . a small fraction of the atoms can and do escape permanently into space.

Tabella: Parametri

Pianeta	**Densità g/cm3**	**Temp.Sup K**	**Gravità Terra =1**	**Vel.fuga m/s**	**Composizione atmosferica**
Mercurio	5.42	440	0.37	4.3	Trace?
Venere	5.25	730	0.89	10.4	CO_2 (96%) +N_2 (3.5%) + SO_2 (130 ppm)
Terra	5.51	288	1.0	11.2	N_2 (78%) + O_2 (21%) +Ar (.9%)
Marte	3.96	210	0.39	5.1	CO_2 (95%) + N_2 (2.7%)
Giove	1.35	152	2.65	60.0	H_2 (86%), H_e (14%), CH_4 (0.2%)
Saturno	0.69	143	1.65	36.0	H_2 (97%), H_e (3%), CH_4 (0.2%)
Urano	1.44	68	1.0	22.0	H_2 (83%), H_e (15%), CH_4 (2%)
Nettuno	1.65	53	1.5	22.0	H_2 (79%), H_e (18%), CH_4 (3%)

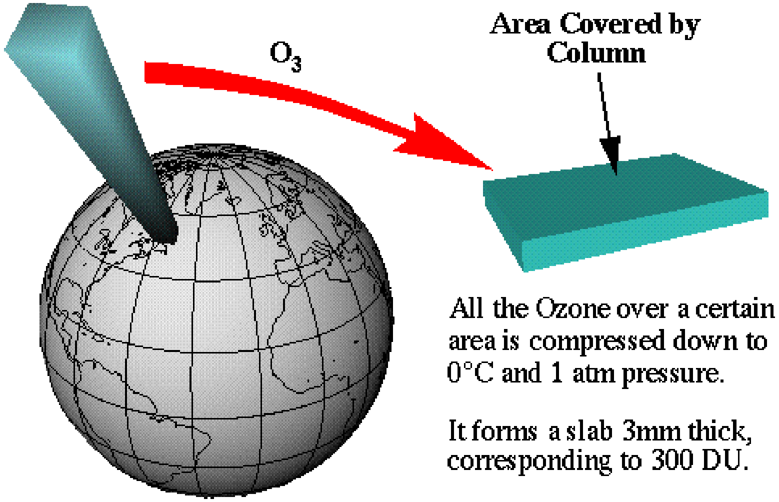
What is ozone?

- Ozone forms a layer in the stratosphere, thinnest in the tropics (around the equator) and denser towards the poles
- measured in Dobson units (DU)
- ~260 DU near the tropics



What is a Dobson unit?

- 1 Dobson Unit (DU) is defined to be 0.01 mm thickness at STP - (0C and 1 atmos press).
- A slab 3mm thick corresponds to 300 DU

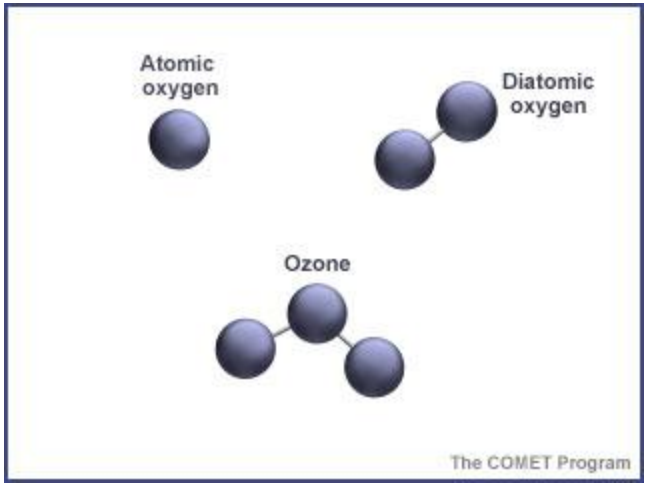


All the Ozone over a certain area is compressed down to 0°C and 1 atm pressure.

It forms a slab 3mm thick, corresponding to 300 DU.

How is ozone formed?

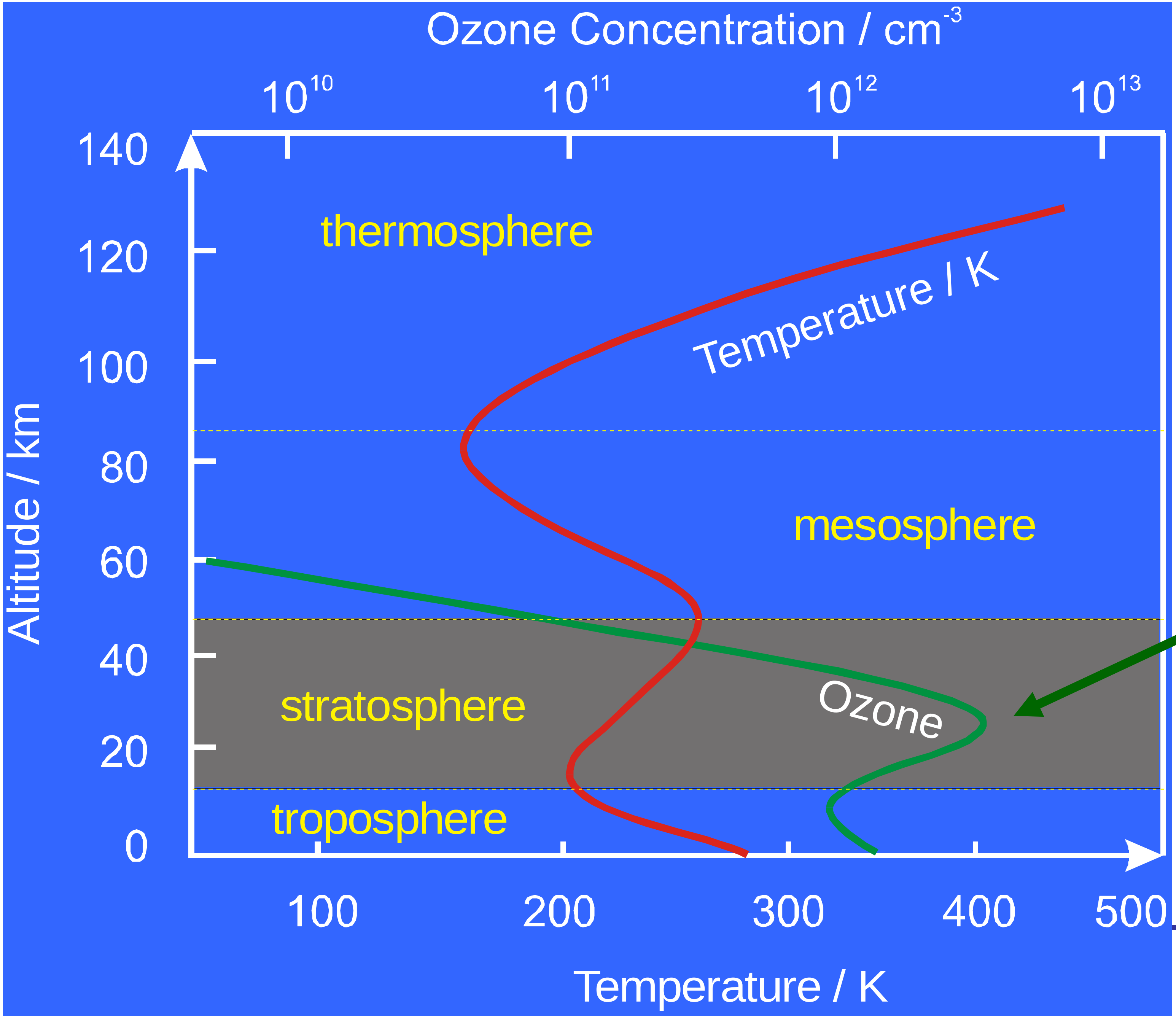
UV radiation strikes the O_2 molecule and splits it, atomic oxygen associates itself with another O_2 molecule – *simplistic version*



Ground level clean air : main constituents

Molecule	**Mole fraction**	**ppmv** (parts per million by volume)
N_2	0.78 *or* 78 %	780900
O_2	0.21 *or* 21 %	209400
H_2O	0.03 (25 °C,100 % humidity) 0.01 (25 °C, 50 % humidity)	31000 16000
Ar	0.01 *or* 1 %	9300
CO_2	3.8×10^{-4} *or* 0.038 %	380
Ne	1.8×10^{-5}	18
CH_4	1.5×10^{-6} ↕ ***Trace gases***	1.5
O_3	2.0×10^{-8}	0.02

The Ozone story : distribution in the stratosphere before ca. 1960

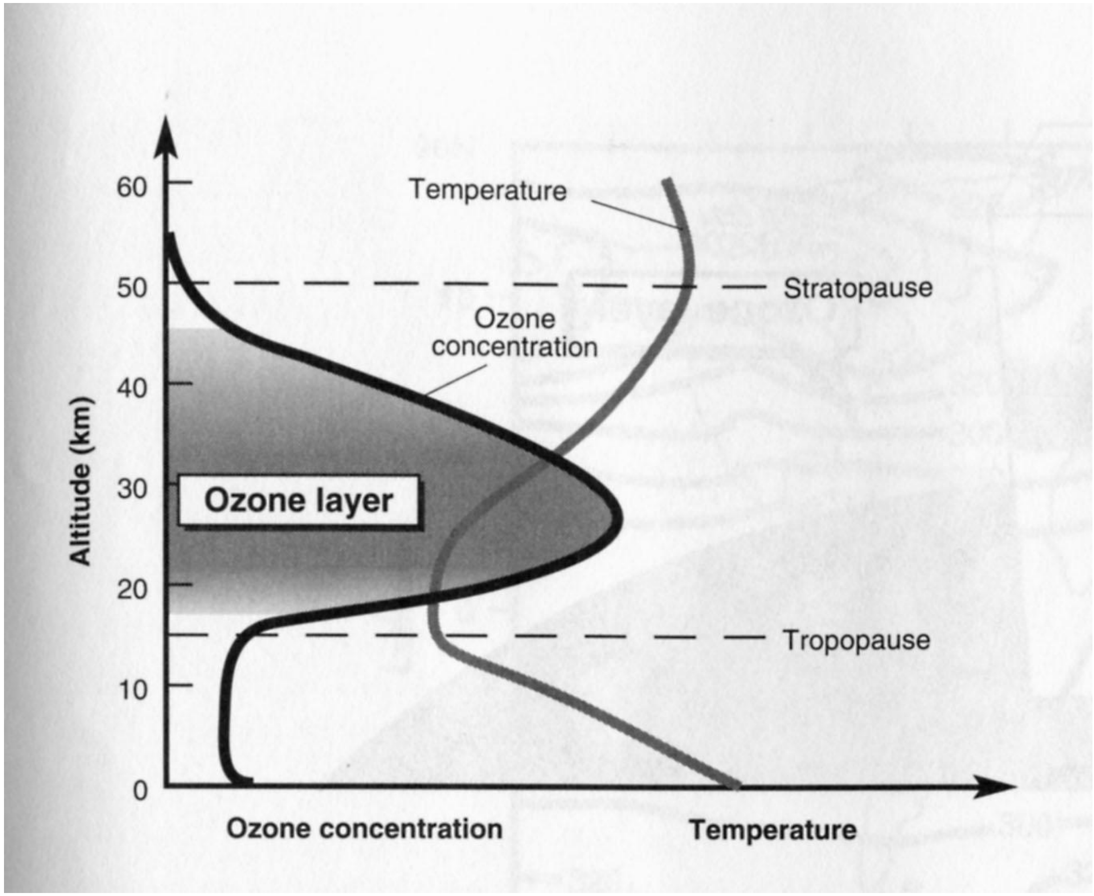


$[O_3]_{max}$ =

4×10^{12} cm^{-3}

at 30 km

Vertical variation of ozone



“Chapman Reactions”

- Ozone is formed by:

$$O_2 + hv \text{ -> } O + O \qquad (1)$$

- Ozone can reform resulting in no net loss of ozone:

$$O_3 + hv \text{ -> } O_2 + O \qquad (3)$$

$$O + O_2 \text{ -> } O_3 \qquad (2)$$

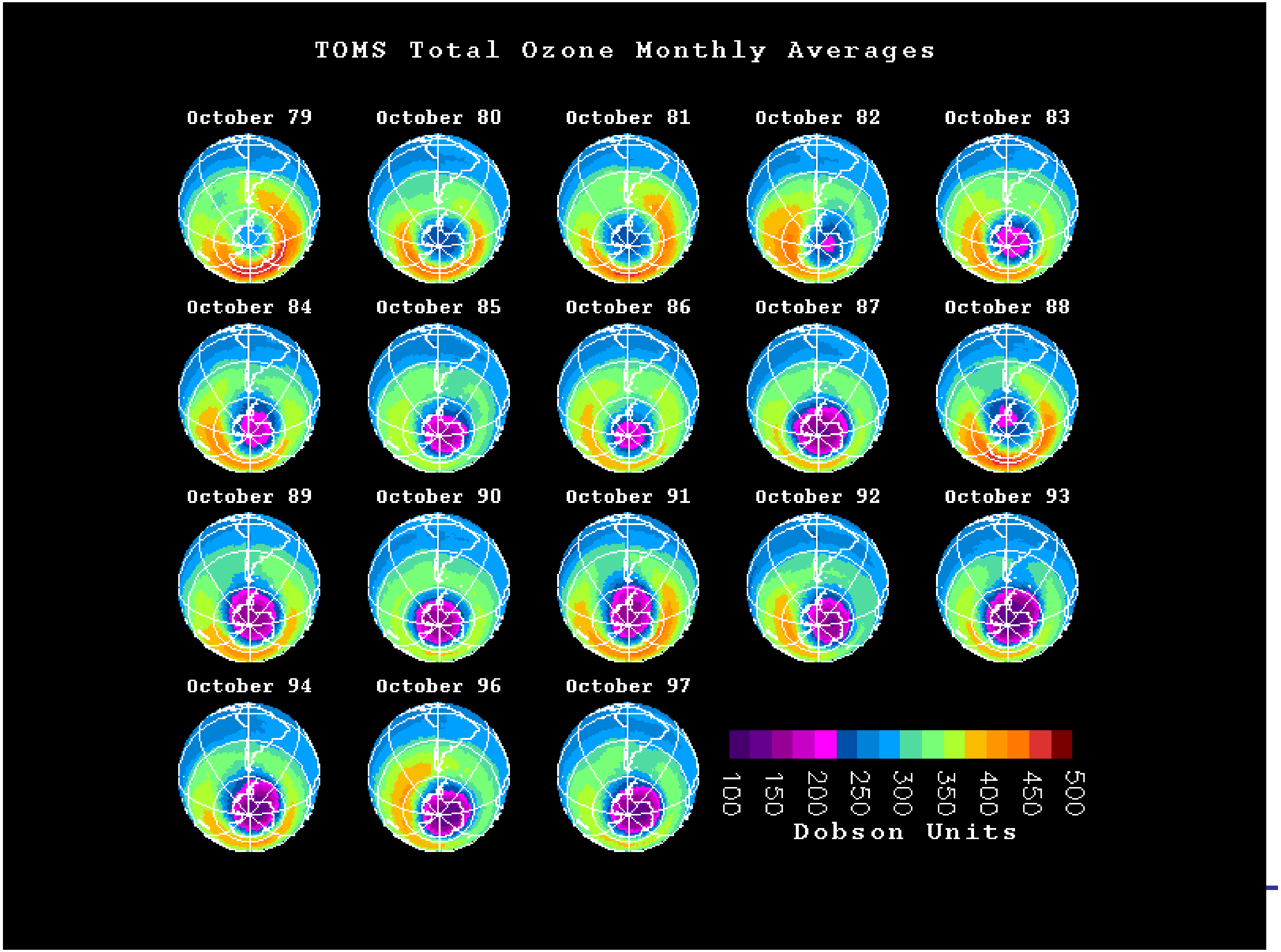
- Ozone is also destroyed by the following reaction:

$$O + O_3 \text{ -> } O_2 + O_2 \qquad (4)$$

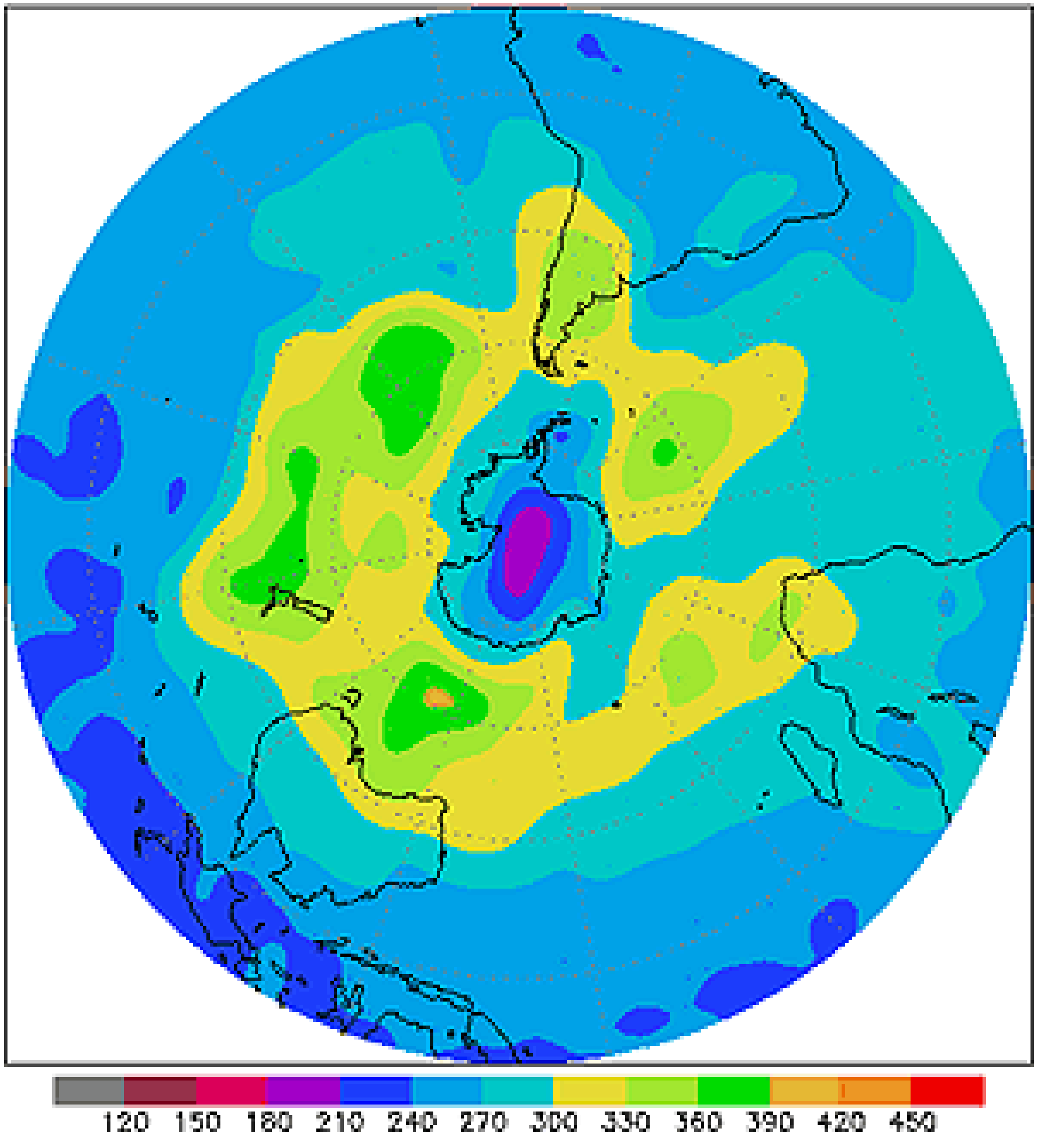
What is the ozone hole?

- News media confuses it with the problem of global warming
- ozone contributes to the greenhouse effect
- over Antarctica (and the Arctic), stratospheric ozone depleted over past 15 years at certain times of the year
- hole presently size Antarctica, 10km altitude - lower stratosphere

Development of Antarctic Ozone Hole, 1979-1997



The Antarctic Ozone Hole


TOVS Total Ozone Analysis (Dobson Units)
Climate Prediction Center/NCEP/NWS/NOAA
08/05/03

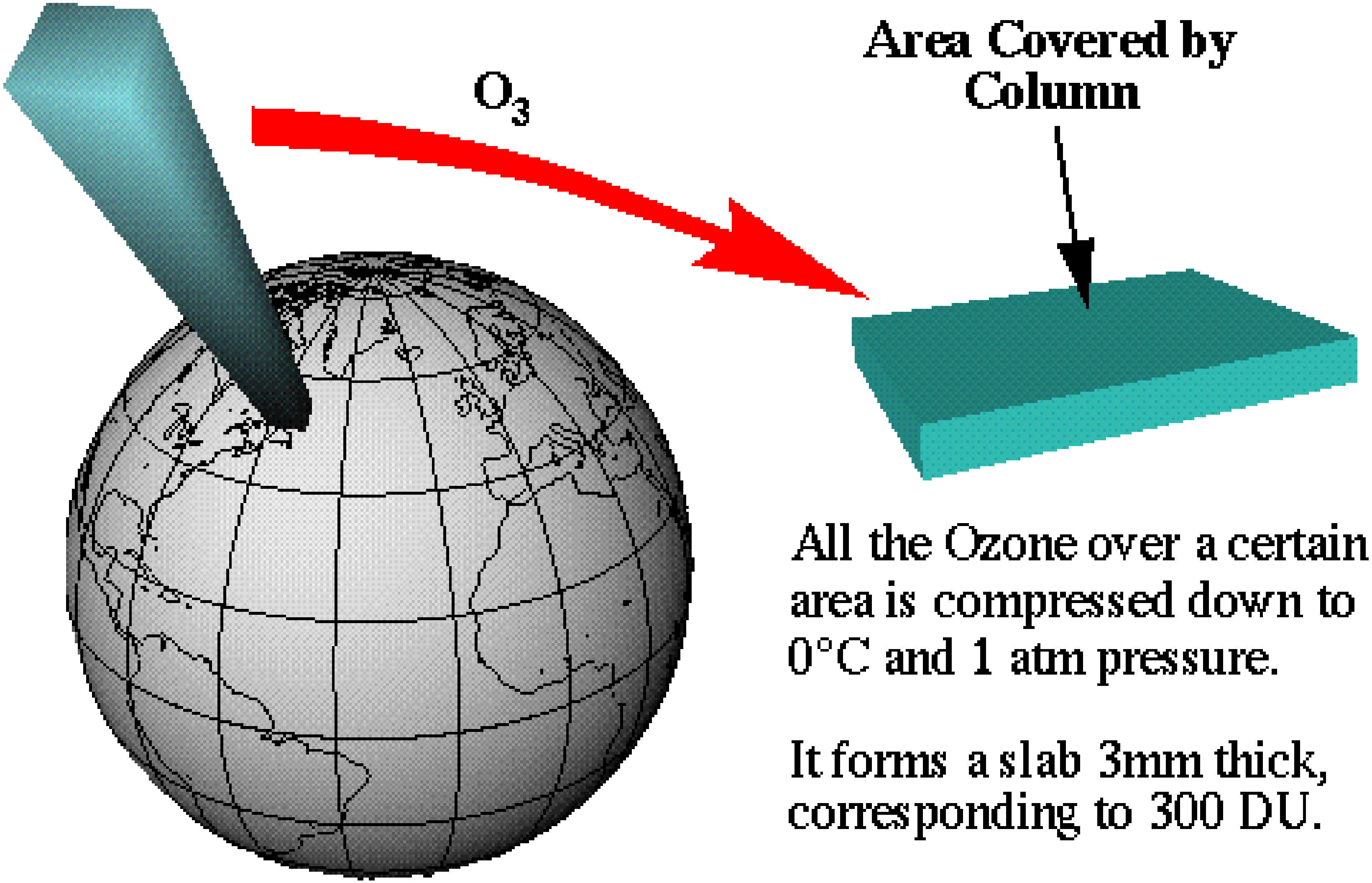
- Antarctic Ozone Levels in Fall 2003

  (Source: NOAA TOVS satellite)
- The ozone hole is represented by the purple, red, burgundy, and gray areas that appeared over Antarctica in the fall of 2003. The ozone hole is defined as the area having < 220 Dobson units (DU) of ozone in the overhead column

The Antarctic Ozone Hole

- The ozone hole is a well-defined, large-scale destruction of the ozone layer over Antarctica that occurs each Antarctic spring.
- The word "hole" is a misnomer; the hole is really a significant thinning, or reduction in ozone concentrations, which results in the destruction of up to 70% of the ozone normally found over Antarctica.

The Antarctic Ozone Hole



All the Ozone over a certain area is compressed down to 0°C and 1 atm pressure.

It forms a slab 3mm thick, corresponding to 300 DU.

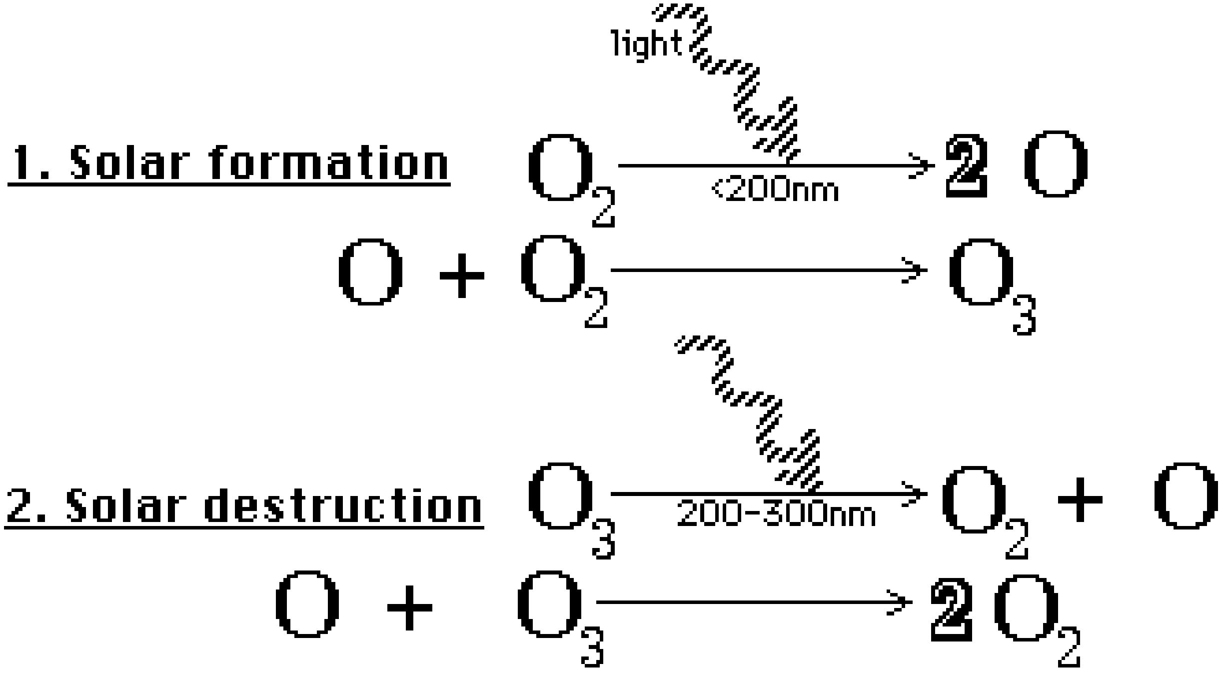
The Antarctic Ozone Hole

- The illustration above shows a column of air, 10 deg x 5 deg, over Labrador, Canada. If all the ozone in this column were to be compressed to standard temperature and pressure (STP) (0 deg C and 1 atmosphere pressure) and spread out evenly over the area, it would form a slab approximately 3mm thick.
- 1 Dobson Unit (DU) is defined to be 0.01 mm thickness at STP; the ozone layer over Labrador then is 300 DU.

  - The unit is named after G.M.B. Dobson, one of the first scientists to investigate atmospheric ozone (~1920 - 1960). He designed the 'Dobson Spectrometer' - the standard instrument used to measure ozone from the ground.
  - The Dobson spectrometer measures the intensity of solar UV radiation at four wavelengths, two of which are absorbed by ozone and two of which are not.

Basic Chemistry of Ozone Depletion

- **Formation and destruction of ozone (**Up to 98% of the sun's high-energy ultraviolet light (UV-B and UV-C) are absorbed)



- The global exchange between ozone and oxygen is on the order of 300 million tons per day.

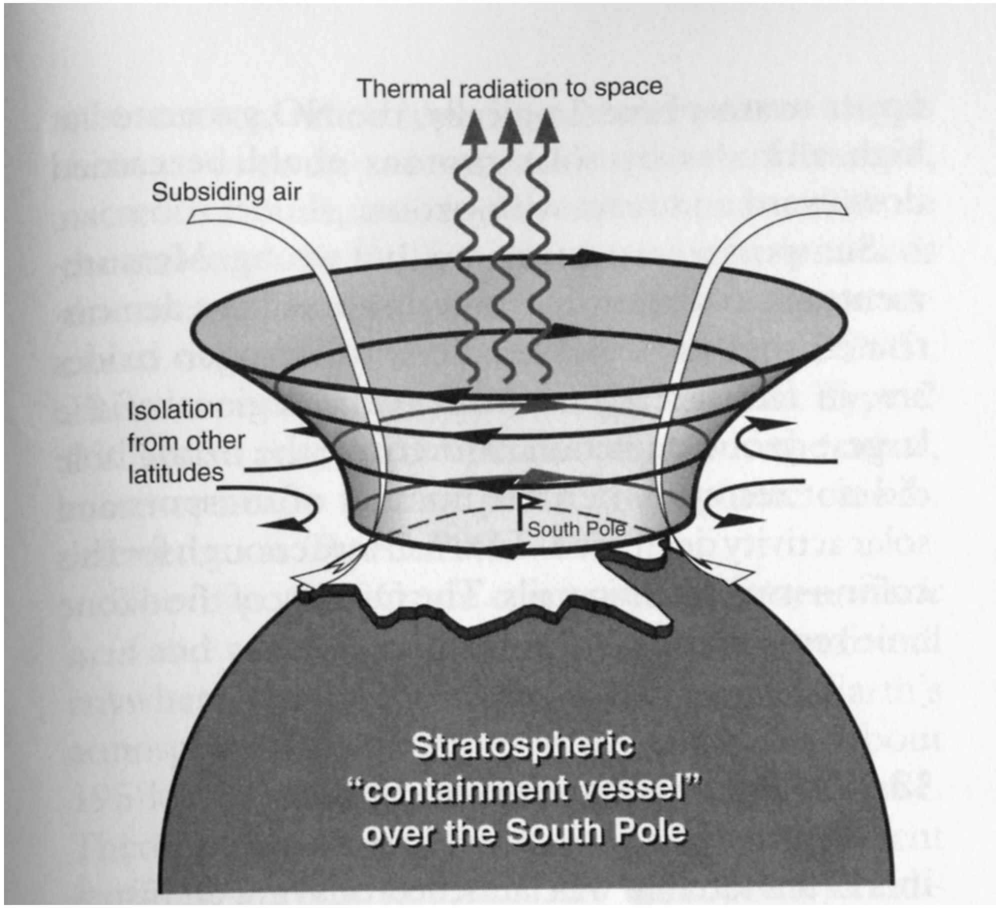
Ozone-Depleting Substances (ODS)

- Ozone-Depleting Substance(s) (ODS): a compound that contributes to stratospheric ozone depletion
- include CFCs, HCFCs, halons, methyl bromide, carbon tetrachloride, and methyl chloroform.
- very stable in the troposphere and only degrade under intense ultraviolet light in the stratosphere.
- When they break down, they release chlorine or bromine atoms, which then deplete ozone.
- Chlorofluorocarbon (CFC, Freon): a compound consisting of chlorine, fluorine, and carbon
- CFCs are commonly used as refrigerants, solvents, and foam blowing agents.

Ozone loss recipe - summary

- Polar winter ➔ polar vortex ➔ isolates air within
- Cold temperatures ➔ Polar Stratospheric Clouds ➔ vortex air isolated ➔ cold temperatures & PSC’s persist
- Heterogeneous reactions allow reservoir species of chlorine & bromine - rapidly converted to more active forms.
- No ozone loss until sunlight returns ➔ production active chlorine ➔ initiates catalytic ozone destruction ➔ ozone loss rapid

The Antarctic polar vortex



Ozone loss over Antarctica

- most dramatic in the lower stratosphere
- nearly all the ozone depleted
- area the size of Antarctica
- many km thick
- most pronounced in spring/October
- persists two months
- December – moves ➔ Falklands, S Georgia, S Am

Why is the loss more dramatic at the poles?

- Polar meteorology
- Polar vortex – winter polar night
- Polar stratospheric clouds (-80C)
- nitric acid trihydrate
- Chemical reactions
  - occur on surface PSC’s
  - Occur very fast