Terrestrial planet atmospheres

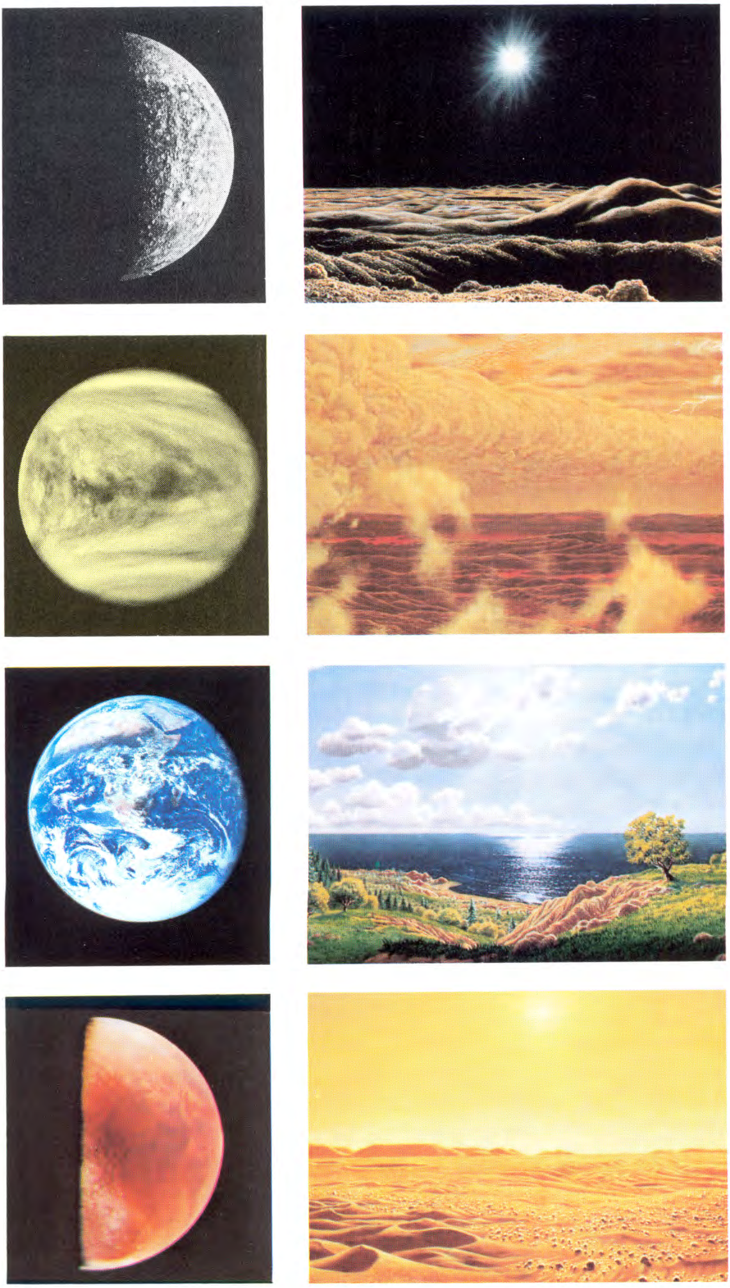
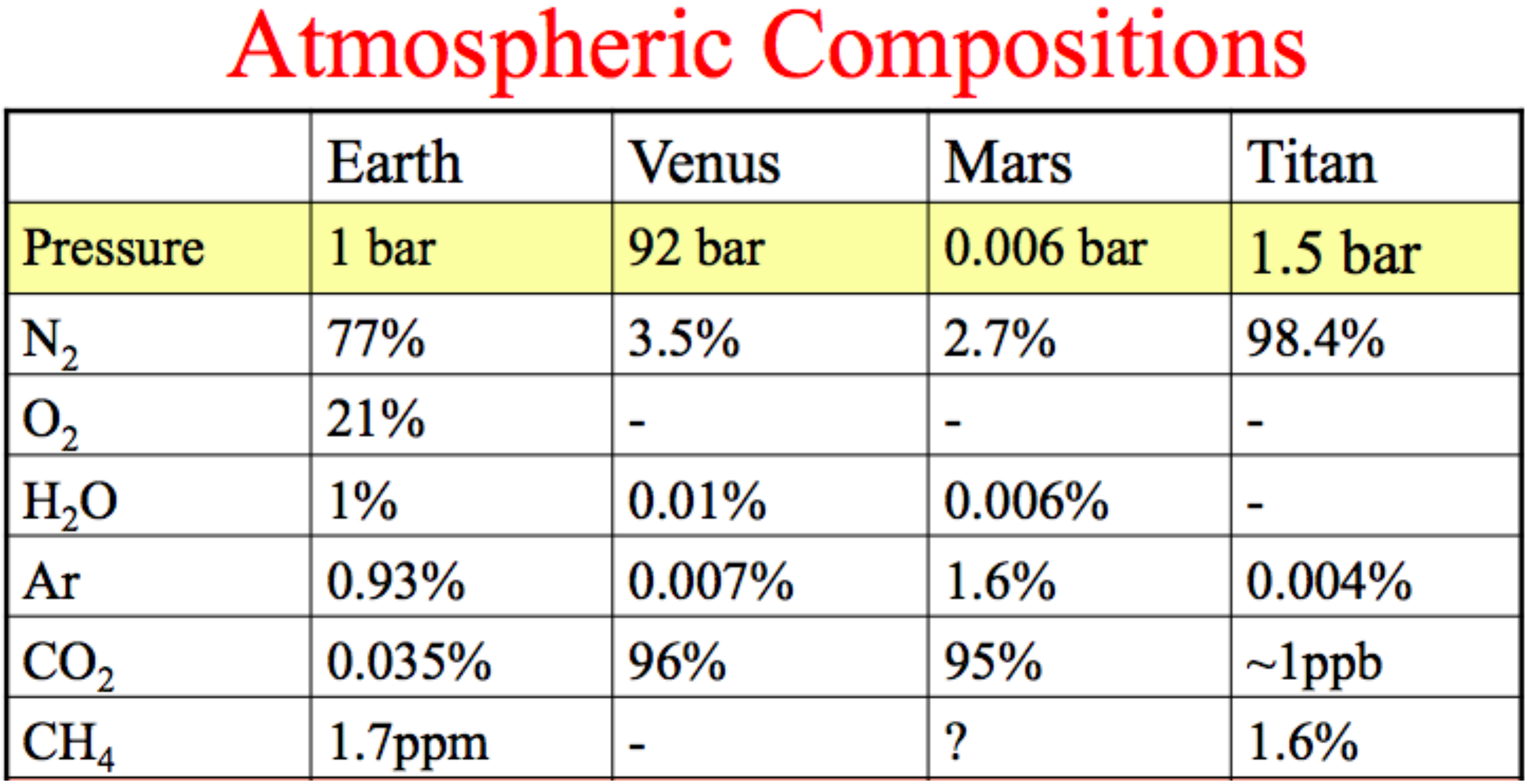


Figure 1. At left are spacecraft photographs of the four terrestrial planets: Mercury from Mariner 10, Venus from the Pioneer Venus orbiter, Earth from Apollo 17, and Mars from the Viking 1 orbiter. Venus appears in a false-color version of an ultraviolet image; its cloud details are not apparent in visible light. White clouds hide about half of Earth at any given time, while clouds of water ice, carbon dioxide ice, and dust enshroud varying portions of Mars. At right, artist Don Davis has portrayed all four terrestrial landscapes as they would appear with the Sun 20° above the horizon.



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%

From Francis Nimmo UCSC

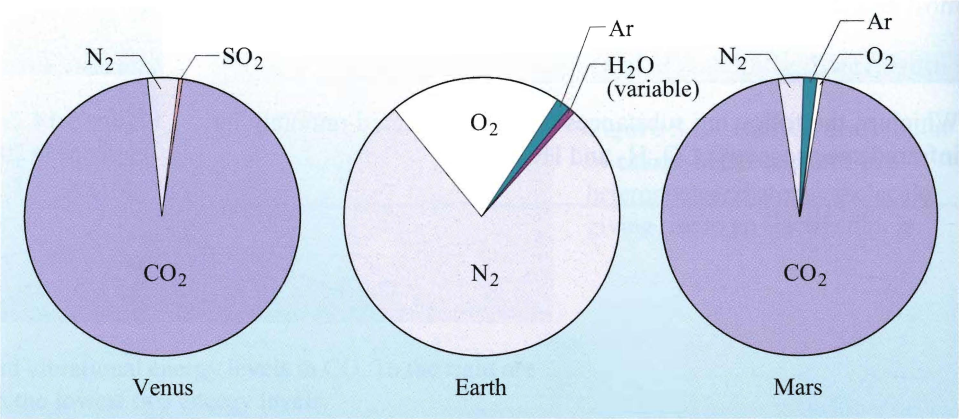


Figure 5.15 The major components of the atmospheres of Venus, Earth and Mars, as measured at the surfaces of the planets. The area of each slice of the pie chart is proportional to the volume ratio of the substance shown.

- Earth, Venus and Mars have quite different atmospheres
- What causes these differences?

(1) Loss of atmosphere (Jeans escape)

(2) Atmospheric evolution (greenhouse effect)

Retaining an atmosphere ("Jeans escape")

Escape velocity : total energy (ke+pe) = 0

$$\frac{1}{2} m v_{esc}^2 = - \frac{GMm}{r}$$

(for particle of mass m at distance R from object of mass M)

$$\text{so} \quad v_{esc} = \sqrt{\frac{2GM}{r}}$$

In order for a molecule to escape from the atmosphere, it must be moving at v_{esc}

Velocity distribution as f(temp) given by Maxwell-Boltzmann distribution.

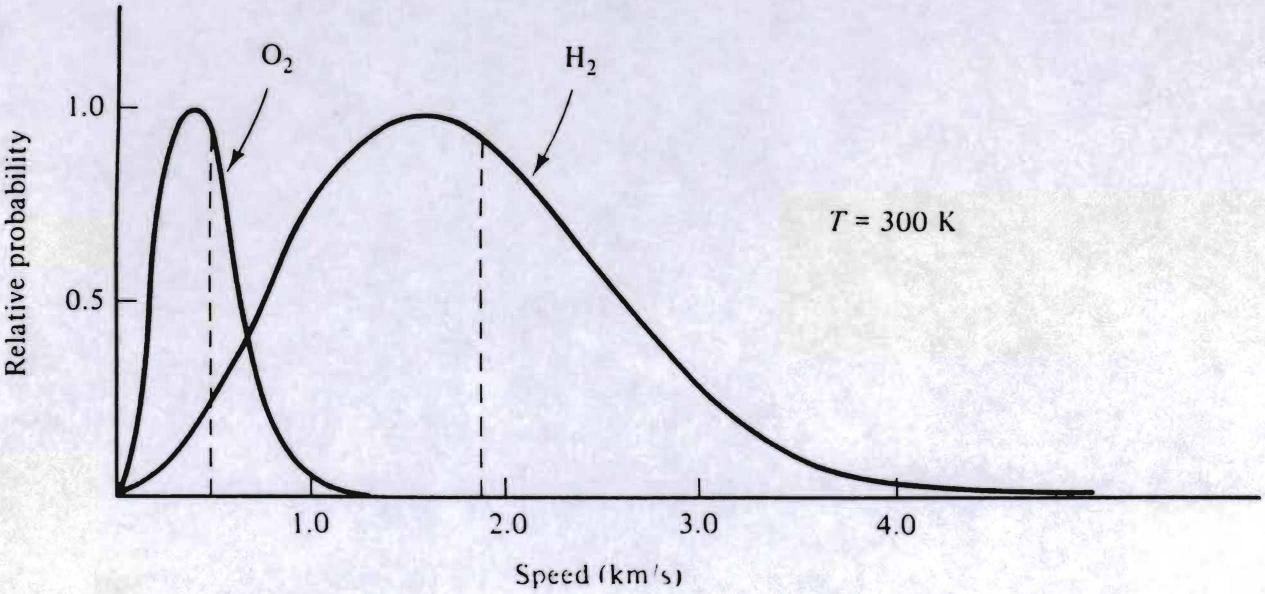


Figure 23.6 Maxwell–Boltzmann distribution for oxygen and hydrogen molecules at $T = 300$ K. For each curve, the vertical axis is a relative probability of finding a molecule at a given speed. In each case, the vertical dashed line is for a molecule whose energy is $\frac{3}{2} kT$. Notice the large number of molecules with greater than this average speed.

Maxwell-Boltzmann distribution for no of particles with speed between v & $v + dv$

$$N(v)\, dv \;\propto\; v^2 e^{-mv^2/2kT}\, dv$$

m = molecule mass

Despite the fact that H and He are the most abundant elements in the universe, only traces of H & He are found in the atmospheres of any terrestrial planet

Q What do you think is causing this?

Median velocity for H_2 atoms at 300k is ~ 2 km/s.

Escape velocity from Earth's surface is 11 km/s

??

But the Maxwell-Boltzman dist^n has a high-velocity tail
AND the early Earth was considerably hotter

Escape velocity

$$v_e = \sqrt{\frac{2GM}{r}}$$

Earth	11 km/s		
Mars	5.1 km/s	Mercury	4.2 km/s
Moon	2.4 km/s		

Mean speed

$$\bar{v} = \sqrt{\frac{2CT}{m}}$$

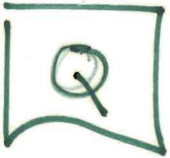
C = heat capacity

at 300 K H_2 has $\bar{v} \approx 2.5$ km/s

O_2 has $\bar{v} \approx 0.6$ km/s

But particles have a range of speeds …….

In age of Solar System, if $\bar{v} \simeq 0.2 v_e$, all molecules escape.



Where does the Earth's atmosphere come from ?

Could it be primordial?

- The amount of Ne in our atmosphere rules this out
- Ne is a heavy inert gas so almost none would escape the Earth’s gravitational pull
- Add other gases from protoplanetary nebula in proportion: we only get about 1% of our current atmosphere
- So our atmosphere wasn’t accreted from the early solar nebula

The present-day atmosphere

The density of the Earth (higher in the mean than the surface rocks) implies that there was a time when the early Earth was molten. Also gases not accreted well by planetesimals with lower mass

Q This implies that any early atmosphere would be lost as the kinetic energy of gas particles would be high and $v > v_{esc}$

So where does our current atmosphere come from ?

→ VOLCANOS and outgassing from rocks

Plate Tectonics help provide the atmosphere as new material is continually being brought up from the mantle

The Earth is remarkable amongst terrestrial planets for its O_2 - rich atmosphere : oxygen is reactive & easily forms chemical compounds.

Plant life + bacteria takes in CO_2 & water, liberate O_2 (energy input from Sun)

Carbonate – silicate cycle

- CO_2 in atmosphere dissolves in rainwater making H_2CO_3
- Rain reacts with rocks containing Ca, Si, releasing Ca^{++} HCO_3^- ions
- In sea, plankton etc incorporate ions in shells ($CaCO_3$)
- Shells settle to sea floor, eventually subducted to interior of Earth
- Heat releases CO_2, comes out

in volcanos, mid-ocean ridges

This process changes as planet's temperature changes.

Q Imagine extreme case of oceans freezing entirely. What would happen?

→ no rainfall 'cos no evaporation from oceans

→ CO_2 builds up in atmosphere

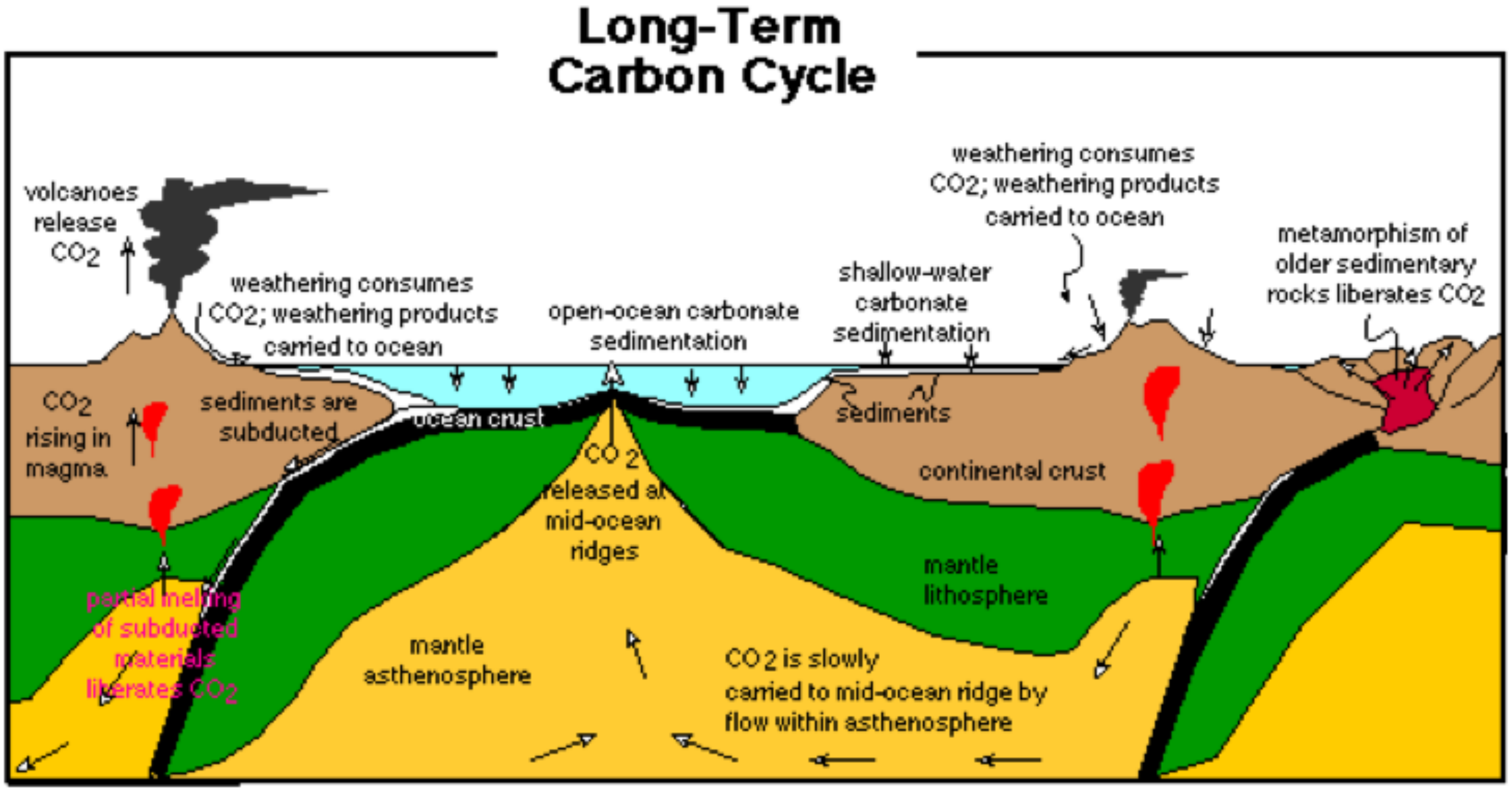


Figure 7.3. Schematic representation of the long-term global carbon cycle showing the flows (hollow arrows) of carbon that are important on timescales of more than 100 Kyr. Carbon is added to the atmosphere through metamorphic degassing and volcanic activity on land and at mid-ocean ridges. Atmospheric carbon is used in the weathering of silicate minerals in a temperature-sensitive dissolution process; the products of this weathering are carried by rivers to the oceans. Carbonate sedimentation exracts carbon from the oceans and ties it up in the form of limestones. Pelagic limestones deposited in the deep ocean can be subducted and melted. Limestones deposited on continental crust are recycled much more slowly — if they are exposed and weathered, their remains may end up as pelagic carbonates; if they get caught up in a continental collision, they can be metamorphosed, liberating their CO_2.

$\boxed{Q}$ With more CO_2 in atmosphere, what happens to surface temperature?

→ Greenhouse effect so temperature rises

→ Oceans melt

And ice caps too!

It is thought that this feedback has kept Earth's temperature constant even when the young Sun gave off ~ 30% less energy

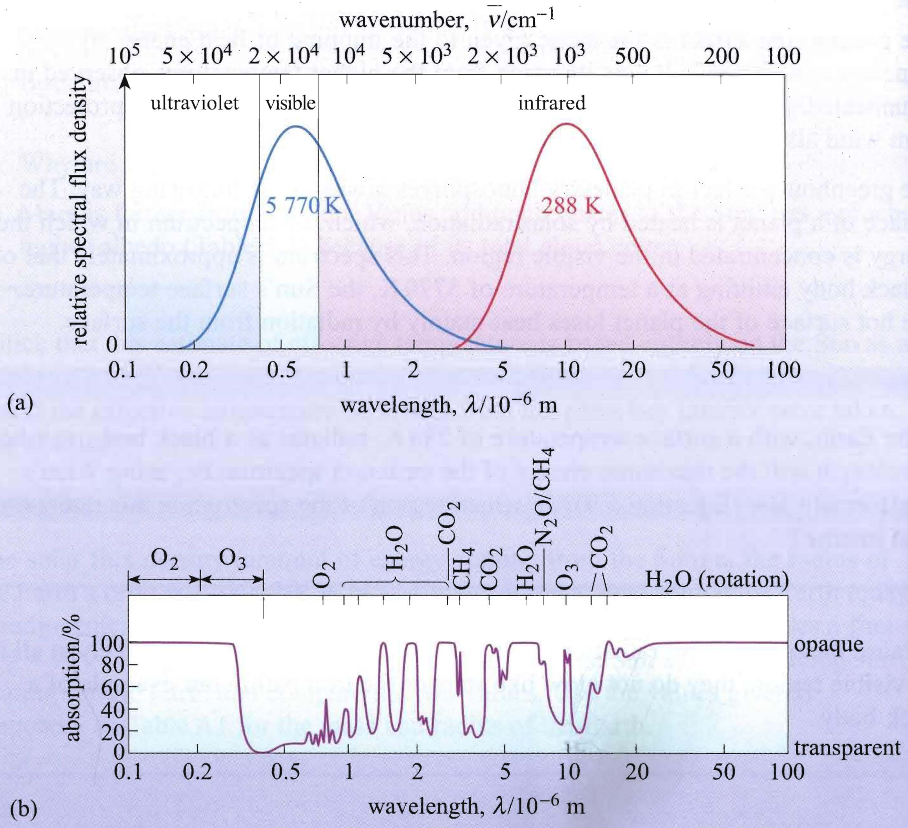


Figure 5.22 (a) Spectra of black-body sources at the temperatures of the Sun's surface (5770 K) and the Earth's surface (288 K). The vertical scales for the two spectra are not the same; the Sun's radiation is much more intense than that of the Earth. (b) The absorption spectrum of the Earth's atmosphere: the wavelengths at which some atmospheric gases absorb energy are indicated.

TABLE 11-2 Inventories of Selected Outgassed Volatiles on Terrestrial Planets (10^{-9} kg/kg planetary mass)

Volatile	Venus	Earth	Mars
H_2O			
Atmosphere	60[a]	3[b]	0.02
Oceans and polar caps	—	250 000[a,b]	5 000?[a,c]
Crust	160 000?[c]	30 000[b]	10 000?[a,c]
Total	160 000?	280 000	15 000?
CO_2			
Atmosphere	100 000[a,c]	0.4[b]	50[a,d]
Polar caps	—	—	10[d]
Crust	—	100 000[a,b]	>900?[e]
Total	100 000	100 000	>1000?
N_2			
Atmosphere	2 000[a]	2 000[a]	300[a]
^{40}Ar			
Atmosphere	4[a]	11[a]	0.5[a]

Note: Entries with two references are averages.

[a] Pollack and Black (1979).

[b] Walker (1977).

[c] Khodakovsky and others (1979).

[d] Hess, Henry, and Tillman (1979).

[e] Fanale and Cannon (1979) estimate 6×10^{17} kg of CO_2 adsorbed in nontronite clays in Martian polar layered terrain and associated regolith, substantially exceeding the CO_2 in the atmosphere or polar caps.