H_2O in the solar system

Water plays a dominant role in what makes the ⊕ geologically distinctive among planets:

- weathering & erosion, presence of sedimentary rocks
- lowers T_{melt} of magmas — probably required for differentiation of continental crust
- lowers rock strength — may be required for plate tectonics
- necessary for life

What about other planetary bodies?

- comets — highly elliptical orbits — composed of ice & dust (dirty snowballs) — may be an important source of H_2O in solar system
- Mercury — no volatiles whatsoever
- Venus — dense atmosphere (100 bars) 96% CO_2, 3.5% N_2 — essentially no H_2O
- Moon — dry
- Mars — tenuous atmosphere — 600 Pa — mostly CO_2 — evidence of past water in surface images, e.g., dendritic stream channels — is it now gone or present in a deep permafrost layer?

Jeans escape law

dissociation in upper atmosphere

$$2H_2O + \text{UV radiation} \rightarrow 2H_2 + O_2$$

mean square velocity of a diatomic gas molecule

$$\frac{1}{2} m \langle v^2 \rangle = \frac{5}{2} kT$$

m = mass
k = Boltzmann's constant
$= 1.38 \cdot 10^{-23}$ J/K
T = temp (°C) + 273 — Kelvins

Multiply by Avogadro's number
$N = 6.022 \cdot 10^{23} \frac{\text{molecules}}{\text{mole}}$

$$\frac{1}{2} M \langle v^2 \rangle = \frac{5}{2} RT$$

where $M = mN$ = mol. weight
$R = kN$ = gas constant
$= 8.31 \frac{J}{K\ \text{mole}}$

$$\boxed{\langle v^2 \rangle^{1/2} = \sqrt{\frac{5RT}{M}}}$$

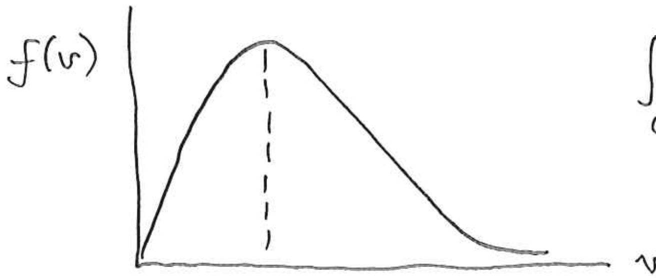
depends only on temperature and molecular weight

Example : H_2 ($M = 2 \frac{\text{gm}}{\text{mole}} = 2 \cdot 10^{-3} \frac{\text{kg}}{\text{mole}}$) at $T = 290$K

$$\langle v^2 \rangle^{1/2} = 2.5 \text{ km/sec}$$

Maxwell – Boltzmann distribution of molecular velocities

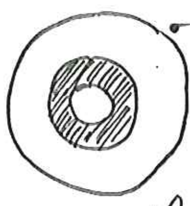
$$f(v) = 4\pi v^2 \left(\frac{m}{2\pi k T}\right)^{3/2} e^{-\frac{1}{2} m v^2 / kT}$$



$$\int_0^\infty f(v)\, dv = 1$$

maximum
at $1.22 \langle v^2 \rangle^{1/2}$

Compare these thermal energies with planetary escape velocities



gas molecule velocity v, mass m

planet mass M
radius R

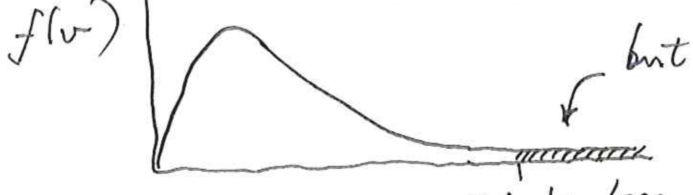
Total energy

$$E = \underbrace{\tfrac{1}{2} m v^2}_{\text{kinetic}} - \underbrace{\frac{GMm}{R}}_{\text{potential}}$$

Escape velocity:

$$\boxed{v_e = \sqrt{\frac{2GM}{R}}}$$

For the $\oplus$ $v_e = 11.1$ km/sec $\Rightarrow$ most H_2 molecules in atmosphere unable to escape



but a few leak out

Planet	v_e (km/s)	T(K)	$\langle v^2 \rangle^{1/2}_{H_2}$ (km/s)	$\dfrac{\langle v^2 \rangle^{1/2}}{v_e}$
Mercury	4.3	700	3.7	0.88
Venus	10.3	740	3.8	0.37
Earth	11.1	290	2.4	0.22
Moon	2.4	380	2.8	1.2
Mars	5.1	240	2.2	0.43

Jeans escape is not the whole story.
Condensation of planitesimals in solar nebula gave rise to volatile-poor inner (terrestrial) planets and volatile-rich (gaseous) outer planets.

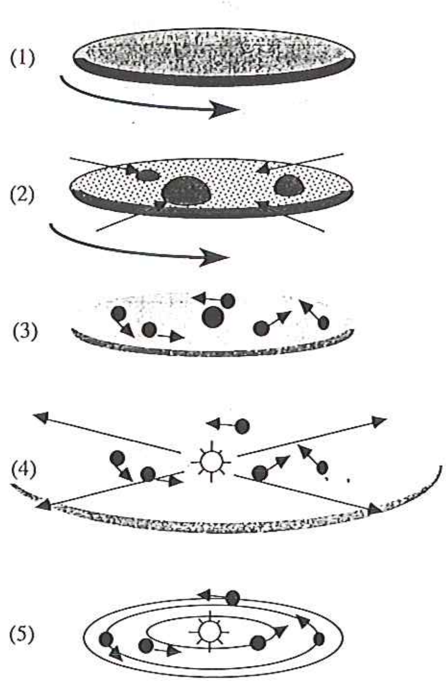


FIGURE 14.3 Five stages in the evolution of the solar nebula. (1) Starting as a disk-shaped cloud of gas and dust. . . (2) the cloud collapsed into fragments. . . (3) that began to orbit about the largest fragment, the proto-Sun. (4) As the Sun ignited, the energy from its solar wind and the pressure of its light combined to blow away the rest of the gas. . . (5) leaving behind rocky planetesimals, which would eventually collide and form into planets.

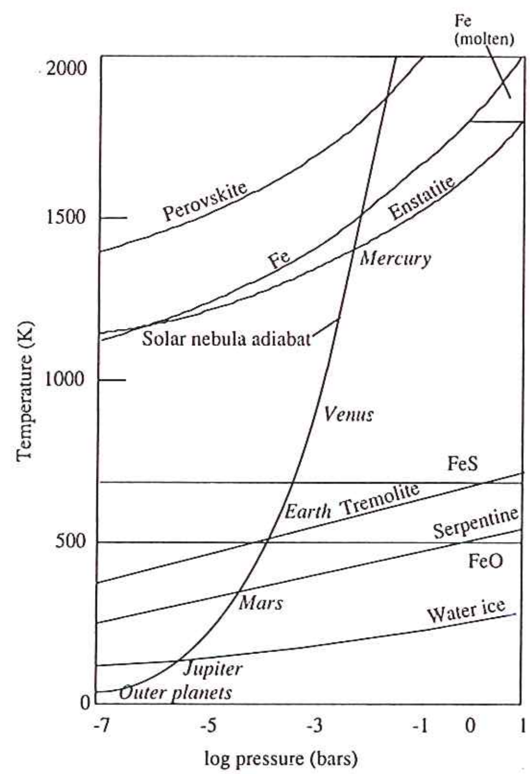


FIGURE 14.4 The equilibrium condensation sequence in a solar nebula. The lines mark the P–T conditions where various representative minerals begin to condense or are formed by a reaction with a preexisting condensate and the gas. An adiabat for the solar nebula is shown, with suggested condensation ranges of each planet, Mercury through Jupiter and the outer planets.

This explains presence of H_2O on Galilean satellites of Jupiter:

Table I: Fundamental Data on the Galilean Moons of Jupiter				
	Io	Europa	Ganymede	Callisto
Mass (MG) (km^3/s^2)	5959.91	3202.86	9886.6	7181
Radius(km)	1821.3	1565	2634[3]	2403
Density (kg/m^3)	3529.13	3018	1936	1852
Moment (I/MR^2) +/-	0.378 0.007	0.330 0.014	0.3117 0.0026	0.359 0.005
Period (d)	1.769	3.551	7.155	16.69
v_e (km/s)	2.6	2.0	2.7	2.4
$\frac{\langle v^2 \rangle^{1/2}_{H_2}}{v_e}$	0.58	0.75	0.56	0.62

[1] assuming $T = T_{Jupiter} = 120\ K$

Inventories of H_2O on $\oplus$ — two Yale estimates

Berner[2]

TABLE 1.1 Inventory of Water at the Earth's Surface

Reservoir	Volume $10^6\ km^3$ (10^{18} kg)	Percent of Total
Oceans	1400.	95.96
Mixed layer	50.	
Thermocline	460.	
Abyssal	890.	
Ice caps and glaciers	43.4	2.97
Groundwater	15.3	1.05
Lakes	0.125	0.009
Rivers	0.0017	0.0001
Soil Moisture	0.065	0.0045
Atmosphere total[a]	0.0155	0.001
Terrestrial	0.0045	
Oceanic	0.0110	
Biosphere	0.002	0.0001
Approximate total	1459.	

Sources: NRC 1986; Berner and Berner 1987.

[a]As liquid volume equivalent of water vapor.

Turekian

TABLE 3–2 Mass of the Present Hydrosphere

	Total Mass (units of 10^{20} g)	Percentage of Total Hydrosphere
Oceans	13,700	80.0
Pore waters in sediments	3,300	18.8
Ice	200	1.2
Rivers, lakes	0.3	0.002
Atmosphere	0.13	0.0008
Total hydrosphere	17,200	100.0