Lecture 9 - Planetary atmospheres

What's Important:
- characteristics of atmospheres
- conditions for retention

Text: Carroll and Ostlie, Chap. 18.3, 21.5

Characteristics of atmospheres

Mercury:
- no atmosphere
- slow rotation of planet with rotational period = (2/3) sidereal orbital period means that side facing the sun bakes at 875 K
- but, polar ice caps at <167 K near the poles, because rotational axis is almost perpendicular to the orbital plane

Venus:
- very dense atmosphere - 96.4% CO_2 and 3.4% N_2; trace amounts of SO_2 and water
- surface pressure = 90 atm and surface temperature = 740 K because of greenhouse effect
- probably once contained a large amount of H_2O, which was driven out by high temperatures; atmospheric deuterium:hydrogen ratio is 0.016, compared to 0.00016 on Earth, suggesting evaporation from upper atmosphere
- surface is highly volcanic, extensive lava flows in last 500 million years

Earth:
- once contained high fraction of CO_2, which was removed to form carbonate rocks (if all of the CO_2 in limestone today were released, atmosphere would resemble Venus)
- Earth is too far away from Sun to have the runaway greenhouse effect of Venus

Mars:
- atmosphere is very thin, 95% CO_2 and 2.7% N_2
- polar caps are also mainly CO_2
- recent observation of extensive water-ice fields
- at earlier times, there may have been more CO_2 in atmosphere (i.e., thicker atmosphere resulting in a higher surface temperature permitting liquid water), but water removed some CO_2 to form carbonate rocks, as on Earth.

Jovian planets:
- atmospheres largely hydrogen and helium
- table below shows the distribution of molecules by number (not by weight) for the upper atmospheres of the Jovian planets

	H_2	He	CH_4	NH_3	H_2O
Sun	86.2%	13.7%			
Jupiter	90%	10%	0.2%	0.02%	0.0001%
Saturn	97%	3%	...		
Uranus	83%	15%	2%		
Neptune	74%	25%	1%		

Note that Saturn is helium deficient. Saturn's largest moon, Titan, has an atmosphere, but Jupiter's moons tend to not to. Nevertheless, water is observed as ice on Jupiter's larger satellites. In order of increasing distance from Jupiter:

Io	volcanic
Europa	surface is a thin and smooth layer of water-ice; displays cracks but not craters, indicating that liquid water is present beneath ice
Ganymede	thick, cratered layer of ice
Callisto	thick, old ice crust

Retention of atmospheres

The ability of a planet to retain an atmosphere reflects a competition between thermal velocity and escape velocity. To establish the criterion for retention, we first discuss the expected temperature of a planet, and then compare the thermal speed of its atmospheric molecules with the escape speed. Several additional features of atmosphere retention, such as the escape rate, are covered in Carroll and Ostlie on p. 771.

Planet temperature

Let's assume that the surface temperature of a planet is determined by the energy it absorbs from its central star. In other words, we ignore contributions such as radioactive decay or tidal heating. If the star has a temperature T_{star} and radius R_{star}, its black-body luminosity is

$$L_{\text{star}} = 4\pi R_{\text{star}}^2 \sigma T_{\text{star}}^4,$$

leading to a flux at a distance D of (L_{star} divided by area of $4\pi D^2$)

$$[\textit{flux}]_{\text{star}} = \sigma T_{\text{star}}^4 \, (R_{\text{star}}/D)^2.$$

The cross sectional area of the planet receiving the light from the star is πR_{planet}^2, so the power received at the planet is

$$[\textit{ideal power}]_{\text{planet}} = \pi R_{\text{planet}}^2 \cdot \sigma T_{\text{star}}^4 \, (R_{\text{star}}/D)^2.$$

Part of this energy is reflected back into space by the surface of the planet. The albedo *a* is the fraction of energy reflected, and 1-*a* is the fraction absorbed. Thus, the net power absorbed is

$$[\textit{net power}]_{\text{planet}} = (1\text{-a}) \cdot \pi R_{\text{planet}}^2 \cdot \sigma T_{\text{star}}^4 \, (R_{\text{star}}/D)^2.$$

If the surface of the planet is at equilibrium, the amount of energy absorbed must equal the amount radiated away. Assuming the planet rotates sufficiently rapidly that the surface temperature is uniform, then an ideal surface obeys

$$4\pi R_{\text{planet}}^2 \sigma T_{\text{planet}}^4 = (1\text{-a}) \bullet \pi R_{\text{planet}}^2 \bullet \sigma T_{\text{star}}^4 \, (R_{\text{star}}/D)^2$$

or

$$4 T_{\text{planet}}^4 = (1\text{-a}) \bullet T_{\text{star}}^4 \, (R_{\text{star}}/D)^2$$

and finally

$$T_{\text{planet}} = (1\text{-a})^{1/4} \bullet T_{\text{star}} \, (R_{\text{star}}/ 2D)^{1/2}. \qquad (9.1)$$

Note the that temperature of the planet is independent of its radius.

Example Carroll and Ostlie (p. 768) quote the average value of the Earth's albedo at $a = 0.3$, so that Eq. (9.1) leads to the prediction $T_{\text{earth}} = 255$ K = -19 °C. While this is not ridiculous, it is a little low. The presence of greenhouse gases in the Earth's atmosphere raises the prediction towards its observed value of +15 °C.

Escape criterion

The escape velocity of a particle v_{esc} is obtained by equating its kinetic energy with (the negative of) its gravitational potential energy. For our planet of mass M_{planet} and radius R_{planet}, the escape velocity of a particle of mass m is

$$mv_{\text{esc}}^2 / 2 = GM_{\text{planet}} m / R_{\text{planet}}$$

or

$$v_{\text{esc}} = (2GM_{\text{planet}} / R_{\text{planet}})^{1/2}. \qquad (9.2)$$

Now, the root mean square speed of a particle in a Maxwell-Boltzmann distribution is obtained from

$$mv_{\text{rms}}^2 / 2 = 3k_B T / 2 \qquad (k_B = \text{Boltzmann's constant} = 1.38 \times 10^{-23} \text{ J/K})$$

or

$$v_{\text{rms}} = (3k_B T / m)^{1/2}. \qquad (9.3)$$

Certainly we could equate v_{rms} with v_{esc} to obtain a criterion for molecular escape from an atmosphere. But this turns out to be overkill: the high-v tail of the distribution will continuously leak out of the atmosphere, to be replaced by particles with lower initial speed as they re-equilibrate. It is found that

$$v_{\text{rms}} > v_{\text{esc}}/6 \qquad (9.4)$$

is good enough for the atmosphere to evaporate. Combining Eqs. (9.2) to (9.4), we find

$$\left(\frac{3k_B T_{esc}}{m}\right)^{1/2} > \frac{1}{6}\left(\frac{2G M_{planet}}{R_{planet}}\right)^{1/2}$$

$$\frac{3k_B T_{esc}}{m} > \frac{1}{36} \bullet \frac{2G M_{planet}}{R_{planet}}$$

$$T_{esc} > \frac{1}{54} \bullet \frac{G M_{planet} m}{k_B R_{planet}}$$

Example Carroll and Ostlie (p. 770) compare the escape velocities of N_2 from the Earth and the Moon.

M_{earth} = 6.0 x 10^{24} kg R_{earth} = 6.4 x 10^6 m $T_{esc} > 3900$ K

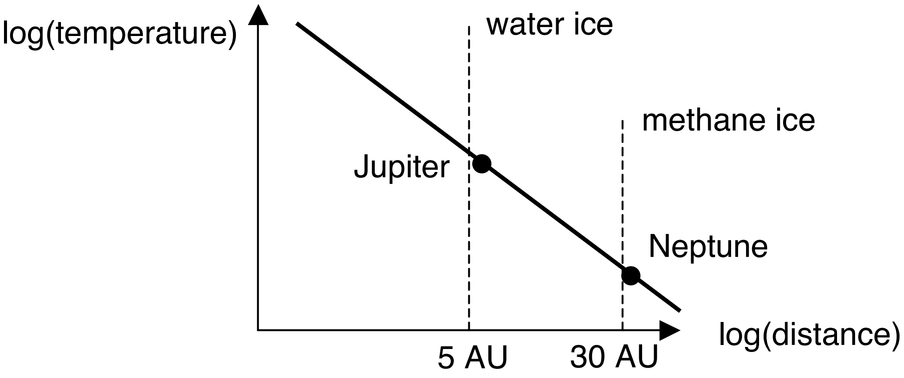
M_{moon} = 7.3 x 10^{22} kg R_{moon} = 1.7 x 10^6 m $T_{esc} > 180$ K

The observed surface temperatures are T_{earth} = 289 K and T_{moon} = 274 K. Even at the top of the atmosphere, the Earth's temperature is 1000 K. Thus, the Earth retains its nitrogen, while the Moon has lost all of its atmosphere.

Scenario for the formation of the solar system

Based on the observed characteristics of the solar system, and the behaviour of stars early in their lives, the following scenario has emerged for the birth of the solar system. In chronological order, the events include:

- condensation of material from a single, spinning disk; most (rotational and orbital) angular momenta are parallel
- planet formation about 4.5 billion years ago
- terrestrial planets lose H/He atmospheres during initial start-up of the Sun, Jovian planets retain atmospheres. Schematically:



- recovery of water on terrestrial planets by cometary bombardment
- end of comet and asteroid bombardment period about 700 million years after planet formation
- beginning of life on Earth shortly after primary bombardment ceases; 3.8 billion year old carbon deposits in Greenland, oldest fossil cells at 3.465 billion years old