Possible Sources of Planetary Atmospheres

- Planetary Nebula (formed w/ planet)
- Released during Accretion
- Released after Accretion - Degassing/Outgassing
- Comets brought volatiles later
- Sublimation from Surface
- Sputtering from Surface

All of these happen/happened, but no single one can explain all planetary atmospheres.

Possible Loss Processes for Planetary Atmospheres

- **Thermal (Jean's) Escape:**
  - Collisionally "equilibrated" gas at a temperature $T$ will have a distribution of kinetic energies (velocities) called a "Maxwellian" or "thermal" distribution:

  ![Graph of Maxwellian distribution]

  $$\text{Kinetic Energy} = \frac{1}{2} m v^2$$
  Peak (most probable) velocity is where
  $$\frac{1}{2} m v_{\text{max}}^2 = k T$$
\[ N_{\text{max}} = \sqrt{\frac{2kT}{m}} \quad \text{most probable speed} \]

If a molecule/atom doesn't collide, and if it has a high enough speed (in the right direction), it can escape the grasp of gravity:

**Escape when:**

\[
\frac{GMm}{r} = \frac{1}{2} m v_{\text{esc}}^2
\]

- \( G = \text{Newton's Universal Gravitational Constant} \)
- \( G = 6.67 \times 10^{-11} \text{ m}^3 \text{ kg}^{-2} \text{ s}^{-2} \)
- \( M = \text{Mass of Planet} \)
- \( m = \text{Mass of molecule/atom} \quad \text{cancels out!} \)
- \( r = \text{distance from center of planet} = R + z \)

So \( v_{\text{esc}} = \sqrt{\frac{2GM}{r}} \)

**For Earth:**

- at surface: \( v_{\text{esc}} = \sqrt{\frac{2GM}{R_e}} = 11.2 \text{ m/sec} \)
- at Exobase (1500 km):
  \[ v_{\text{esc}} = \sqrt{\frac{2GM}{R_e + 1500 \times 10^3}} = 10.7 \text{ m/sec} \]
- So for escape to occur, \( N \geq N_{\text{esc}} \). This is true for some part of the Maxwellian distribution (tail).

- We know the equation for the Maxwellian Distribution (too much math for now) so we can actually calculate how much of a "thermalized" gas will escape per unit time \( \Rightarrow \) Escape Flux.

- The Escape Flux depends on the mass & temperature of the gas.

  - Hotter gases have more population in tail of Maxwellian \( \Rightarrow \) more can escape.

  - Lighter gases have higher speeds for a given temp (distrib shifted).

\[
N_{\text{max}} = \sqrt{\frac{2kT}{m}} \quad \text{if } m \text{ lighter, then } \frac{1}{m} \text{ larger.}
\]

\( \Rightarrow \) So more is \( \Rightarrow N_{\text{esc}} \).
Non-Thermal Escape Mechanisms

- Hydrodynamic Escape - upward flow of lighter gases can "drag" heavier gases up and out.

- Non-thermal "heating" via:
  - charge exchange
  - dissociative recombination
  - impact dissociation
  - photodissociation
  - ion-neutral reactions
  - knock-on (heavy-light collisions)

These make "enhancements" to tail of Maxwellian for certain species.

- Sputtering / Impact Erosion
  - impacts of objects can "blow" atmospheric gases away
  - can be small impacts on surfaces of Mercury/Moon or even impacts of things onto atmosphere itself
  - can also be large impacts (asteroids) simply blowing surface material & entrained gases into space

- Solar Wind Pickup
  - Ions can be swept into space by solar wind along open field lines
  - can be more indirect w/ions moving into magnetosphere, then drifting across field lines to enter solar wind, or colliding w/electrons & recombining to be neutral then escaping.

- Transport into other reservoirs ("hiding")
  - oceans, crust, ice caps, life,...
Current Atmospheres are a result of time-dependent history of these source & loss processes over ~4.65 billion years.

Note: the rate of escape of a gas by any of these processes has limiting factors (bottlenecks)

⇒ For instance, Earth's escape works from the top of the atmosphere (exobase), but you have to get the gas to the top of the atmosphere before some of it can escape.

Analogy: - 2 buckets of water, both with holes.
- Bucket A leaks into Bucket B at a slow rate (small leak)
- Bucket B leaks at a fast rate into drain.

⇒ Anything that goes into B will leak out quickly, but since A is only source to B, the rate of A limits the total leak to drain.
- Remember a few weeks ago we talked about "saturation" and partial pressures of water in air? The above plot shows the partial pressure of H$_2$O for saturation at a given temp as the thick line.

  example: $T = 300$ K $\Rightarrow$ H$_2$O vapor pressure is 30 bar.
Look at Earth

A. Assume early Earth outgassed lots of water and CO₂. Sun gave planet a temp.

B. As gases built up, the greenhouse effect caused the temp. to increase, allowing more H₂O to be gas.

C. Before the temp could increase too much, the saturation point of H₂O vapor was hit.

Any extra water outgassed would mean have to be put into liquid form

⇒ Earth has huge oceans.
Look at Venus:

A. Assume early Venus also outgassed $\text{H}_2\text{O}$ and $\text{CO}_2$. Sun gave Venus a hotter temp. than Earth or Mars to begin with.

B. As gases built up, greenhouse effect increased temp. even more.

C. Venus never hit the saturation line, so all $\text{H}_2\text{O}$ would have stayed as gas, keeping temps really high.

$\Rightarrow$ "Runaway Greenhouse"
So here's the picture:

- Assume Venus & Earth started out with similar amounts of CO₂ and H₂O in their total bulk composition.

- On Earth the initial greenhouse effect wasn't enough to keep the H₂O as a gas, so it condensed out as liquid water, making oceans. Oceans could remove CO₂ from the atmosphere, putting it in rocks.

  ⇒ Earth ended up with little CO₂ or H₂O in atmosphere, but an abundance of it in rocks (CO₂) and oceans (H₂O).

- On Venus the initial temps were high enough that H₂O stayed a gas and CO₂ and H₂O made a huge greenhouse effect making it even hotter, thus guaranteeing that any H₂O would remain a gas.

  ⇒ Venus had a runaway greenhouse so no oceans could form and all CO₂ and H₂O stayed in the atmosphere.
But Venus has almost no \( \text{H}_2\text{O} \) right now?!

If it had it, what happened to it?

First, why do we think Venus had much \( \text{H}_2\text{O} \) to begin with?

Arguments against Venus having lots of \( \text{H}_2\text{O} \):

- Venus closer to Sun, so less \( \text{H}_2\text{O} \) could condense out of solar nebula to make planet
- Venus doesn't need \( \text{H}_2\text{O} \) to make current greenhouse (\( \text{CO}_2 \) was enough)
- If \( \text{H}_2\text{O} \) came from comets, maybe flux of comets was less the closer you get to the Sun.

Other than the middle argument, the statements really just say 'Venus may have started with less water than Earth, but not necessarily so much less.'

Let's just assume it did have quite a bit of water and think about what would happen over 4.65 Billion years.
- 1st we know any H₂O would have stayed as a gas
- UV sunlight can fairly readily break apart H₂O gas to make H and O atoms.
- H is a really light gas, and can readily escape from the top of the atmosphere.

- If no other gases present, the H lifetime of H on Venus due to Jean's escape would be ~ 5.7 x 10⁵ sec
  (Note 4.65 x 10⁹ years = 1.47 x 10⁷ sec)

- But since lots of CO₂ was/is also present, and since not all H₂O was photolyzed (broken apart) immediately, the loss of H would be much slower, but still enough to get rid of lots of H₂O over 4.65 Billion years.

- How can we be sure?
  Look at D/H ratios!

  D = deuterium (heavy hydrogen)
  H = hydrogen (proton + electron)
Solar nebula consisted of a certain fraction of $\Omega/H$ ($\sim 2 \times 10^{-5}$)

Venus atmosphere, if still has same amount of $\Omega$ as began with would have $\Omega/H \sim 2 \times 10^{-5}$

but actually it is $1-2 \times 10^{-2}$

so more $\Omega$ than there should be!

(By a factor of 1000)

$\Rightarrow$ H escaped, but $\Omega$ didn't
(at least not as fast, being twice as heavy)

$\Rightarrow$ Venus started with $\Omega/H$ like nebula, but H escaped

(Note: Earth $\Omega/H = 1.6 \times 10^{-4}$)