If you remember this…. 

- **X-rays**
  - X rays ionize (knock electrons off) almost any gas and dissociate (break apart) molecules when they are absorbed.

- **Ultraviolet**
  - Ultraviolet photons dissociate molecules when they are absorbed.

- **Visible**
  - Most visible-light photons are simply transmitted, though some are scattered. Blue light is scattered more than red light.

- **Infrared**
  - Infrared photons are absorbed by molecules, causing them to vibrate and rotate.

... then you can understand the entire structure of a planet’s atmosphere.
Earth's Atmospheric Structure

**Troposphere:**
- lowest layer of Earth's atmosphere
- Temperature drops with altitude
- Warmed by infrared light from surface and convection
  - Weather!

**Stratosphere:**
- Temperature rises with altitude in lower part, drops with altitude in upper part
- Warmed by absorption of ultraviolet sunlight by ozone
  - Upper levels are too diffuse to absorb UV radiation

**Thermosphere:**
- Layer starting at 80 km altitude
- Temperature rises with altitude
- X-rays from the Sun heat and ionize gases
  - (Top edge actually known as ionosphere)

**Exosphere:**
- Atmosphere gradually fades into space
- Temperature rises with altitude
  - atoms can easily escape into space
- Warmed primarily by X-ray light
  - Very low density, so most light gets through
Clicker Question

Where does the greenhouse effect occur?

A. In the Stratosphere  
B. In the Troposphere  
C. In the Exosphere  
D. In the Lithosphere  
E. In the Thermosphere

Clicker Question

What would the temperature curve look like if Earth had MORE greenhouse gases?

A. The line in the troposphere would go straight up  
B. The line in the troposphere would go to even higher temperatures at low altitudes  
C. The bump in the stratosphere would be even warmer  
D. The bump in the stratosphere would be cooler  
E. The temperature in the thermosphere would be warmer
Comparing the atmospheric structure of different planets

- Consider the effects of:
  - Distance from the Sun
  - Reflectivity
  - Greenhouse gases
  - UV-absorbing gases

Clicker Question

What would happen to Earth’s temperature if it had a much larger reflectivity (but still had the same amount of greenhouse gases)?

A. The temperature would go up (warmer)
B. The temperature would go down (colder)
C. The temperature wouldn’t change

Planetary temperatures

- In the absence of greenhouse gases, how would a planet’s average surface temperature depend on:
  - Size?
  - Distance from the Sun?
  - Rotation Rate?
How would Earth’s climate be different with no greenhouse gases?

- **Obvious difference?**
  - Surface would be colder (below freezing)

- **Subtle differences?**
  - Weather would be much different (Greenhouse effect causes atmospheric convection)

**Planetary temperatures**

In the absence of greenhouse gases, a planet’s average surface temperature depends on:

- **Size?**
  - Not really [external factors dominate - see below]

- **Distance from the Sun?**
  - Absolutely, closer means more!

- **Rotation Rate?**
  - Not really:
    - (Rotation rate can affect day/night differences, but we’re looking at averages)

- **Reflectivity**
  - How much light it reflects away

**“No Greenhouse” Temperatures**

<table>
<thead>
<tr>
<th>World</th>
<th>Average Distance from Sun (AU)</th>
<th>Reflectivity</th>
<th>“No Greenhouse” Average Surface Temperature</th>
<th>Actual Average Surface Temperature</th>
<th>Greenhouse Warming (actual temperature minus “no greenhouse” temperature)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mercury</td>
<td>0.387</td>
<td>12%</td>
<td>163°C</td>
<td>425°C (day), -173°C (night)</td>
<td>—</td>
</tr>
<tr>
<td>Venus</td>
<td>0.723</td>
<td>75%</td>
<td>-49°C</td>
<td>40°C</td>
<td>510°C</td>
</tr>
<tr>
<td>Earth</td>
<td>1.00</td>
<td>29%</td>
<td>-16°C</td>
<td>15°C</td>
<td>51°C</td>
</tr>
<tr>
<td>Moon</td>
<td>1.00</td>
<td>12%</td>
<td>-2°C</td>
<td>125°C (day), -173°C (night)</td>
<td>—</td>
</tr>
<tr>
<td>Mars</td>
<td>1.524</td>
<td>16%</td>
<td>-58°C</td>
<td>-50°C</td>
<td>6°C</td>
</tr>
</tbody>
</table>

- Only two things matter for “No Greenhouse” temps:
  - The planet’s distance from the Sun
  - The planet’s overall reflectivity

**Why the sky is blue?**

- **Atmosphere scatters blue light from Sun, making it appear to come from different directions**

- **Sunsets are red because nearly all the blue light has been scattered away**
Effects of Atmosphere

Gaining vs Losing

- Atmospheric Sources and Losses
  - How do planets gain and lose gases?
- How did these sources and losses explain what happened to Mars and Venus?

Atmospheric Sources

- Outgassing - mainly H₂O and CO₂ (some N₂ and sulfur gases)
- Evaporation / Sublimation
- Surface Ejection

Planets - Double Hump

Visible Sunlight IN

Absorbed Sunlight

IR Thermal Emission OUT

Transmission
Absorption
Scattering
Reflection from clouds

Energy IN
Energy OUT
Volcanic Outgassing - main source of larger terrestrial planet atmospheres ... but not the whole story!

Clicker Question

What would Earth be now if there had never been volcanoes?

A. It would not have the same type of life
B. It would not have much of an atmosphere
C. It would be colder than it is now
D. It would be warmer than it is now
E. A + B + C

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Atmospheric Losses
Clicker Question

Under what circumstances is thermal escape likely to be most active?

A. Light gases on big planets far from the Sun
B. Heavy gases on big planets far from the Sun
C. Light gases on small planets near the Sun
D. Light gases on small planets far from the Sun
E. Equally well on any kind of gas from any kind of planet

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Now that we’ve got the background...

• Let’s find out how these sources and losses explain what happened to Mars and Venus.
• And why didn’t Earth end up like one of them?

Mars

• 0.6% of Earth’s atmospheric pressure
• Primarily CO₂
• Temperature -20 to -50°C

Polar ice cap is water ice and frozen CO₂ (dry ice)
Phoenix lander recently found water ice close to the surface
Sunset image showing a little sunlight scattering
Early days of the Red Planet

First 1-2 billion years:

• warm interior
  - Results in tectonics, volcanoes, & outgassing
    ⇒ Greenhouse effect
    ⇒ Warming the planet enough for liquid water
      ⇒ Oceans
      ⇒ Weather/Erosion
      ⇒ Life???
  • But then Mars cools down...
    - Why?
    - What happens?

(Small) SIZE as the critical factor which determined early cooling and triggered atmospheric loss

A chain of events..... :

• Cold (solid) interior ⇒ loss of magnetic field
  - solar wind stripping steals atmosphere
• Cold interior ⇒ loss of volcanism
  - No gas replenishment
• No atmosphere ⇒ no protection from Solar UV/X-rays
  - $\text{H}_2\text{O}$ broken apart (H escapes, O makes rust)
• Less greenhouse effect ⇒ condensation
  - Gas freezes out
    • Increasing reflectivity
  ***Can no longer support liquid water on surface.***

Clicker Question

What could happen if Mars (today) was moved to Earth’s orbital distance?

A. Greenhouse effect would develop, leading to a pleasant (Earth-like) climate
B. Runaway greenhouse would develop, Mars would be too hot to live on.
C. Polar caps would melt into oceans, leading to a stable climate
D. Some increase in its surface temperature, but still too cold for life
E. No change at all

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Venus: Sister Planet or Evil Twin?

- Large as Earth
  - Ongoing volcanism & outgassing
    - plenty of greenhouse gases
  - High gravity to hold on to atmosphere
  This led to a greenhouse effect (GHE)
    - Which led to high surface temps
      - Also helped by closeness to Sun
- High temps ⇒ steam instead of water ⇒ more GHE ⇒ higher temps ⇒ more steam ⇒
  ⇒ RUNAWAY greenhouse effect!!!(Positive Feedback)

Clicker Question

What is the main reason Earth’s atmosphere contains only small amounts of CO₂?

A. Earth’s volcanoes did not outgas as much carbon dioxide as those on Venus and Mars
B. Plant life converted most of the CO₂ to oxygen
C. Chemical reactions with other gases destroyed the CO₂ and replaced it with the nitrogen
D. CO₂ dissolves in water and most of it is now contained in the oceans and carbonate rocks
E. Earth’s distance from the Sun allowed for the CO₂ to escape
Clicker Question

What is the main reason Earth’s atmosphere contains only small amounts of CO$_2$?

A. Earth’s volcanoes did not outgas as much carbon dioxide as those on Venus and Mars
B. Plant life converted most of the CO$_2$ to oxygen
C. Chemical reactions with other gases destroyed the CO$_2$ and replaced it with the nitrogen
D. CO$_2$ dissolves in water and most of it is now contained in the oceans and carbonate rocks
E. Earth’s distance from the Sun allowed for the CO$_2$ to escape