Upcoming - New HW to be handed out Thurs, due Thurs 3/6
Semester Team project details coming out Tues
Show OH - Grades for Quiz #1, Venus and Vesta pole

Recall: Venus
- 0.815M⊕, 0.95R⊕
- 0.72 AU from Sun
- Orbit: 224d
- Rotation: -243d
- "Sol" (Sunrise-Sunrise): 117d
- Obliquity: 178°
- Albedo: 0.72 - Global H₂SO₄ clouds
- Te = 238K
- Tsurf = 750K

Pressure: 9.2 bar
- (96.5% CO₂, 3.5% N₂,
  150 ppm SO₂, 70 ppm Ar,
  20 ppm H₂O...)
- Very Efficient Greenhouse

Atmos. circulation:
- Lower atmos.
  2 Hadley Cells
- Surface winds ~ 0-1 m/SEC
- Cloudtops (~65 km)
  ⇒ Supernotation ~100 m/SEC
- Upper atmos.
  all in same direction
  (upper atmos. rotates in ~4d)

OH: Venus Y pattern
& S. polar vortex
ASTR/ATOOC 3720 Quiz#1 Grades

Mean = 84.4
Median = 89

98-100 A+
94-97 A
89-93 A-
85-88 B+
80-84 B
76-79 B-
72-75 C+
68-71 C
65-67 C-
50-64 D
<50 F
Venus in UV showing Y-pattern in Clouds

Venus South Polar Vortex
Let's compare Venus & Earth in terms of current atmospheres:

<table>
<thead>
<tr>
<th>Species</th>
<th>Venus</th>
<th>Earth</th>
<th>Earth hidden</th>
</tr>
</thead>
<tbody>
<tr>
<td>All</td>
<td>100% (92 bar)</td>
<td>100% (1 bar)</td>
<td>160 bar</td>
</tr>
<tr>
<td>CO₂</td>
<td>96.5% (87 bar)</td>
<td>330 ppm (0.33 mbar)</td>
<td>~60 bar (rocks, oceans)</td>
</tr>
<tr>
<td>N₂</td>
<td>3.5% (3.2 bar)</td>
<td>4% (0.48 bar)</td>
<td>-</td>
</tr>
<tr>
<td>H₂O</td>
<td>2ppm (1.8 mbar)</td>
<td>1% (0.1 mbar)</td>
<td>~100 bar (oceans)</td>
</tr>
<tr>
<td>O₂</td>
<td>20ppm (&lt;1.8 mbar)</td>
<td>20.9% (0.21 bar)</td>
<td></td>
</tr>
<tr>
<td>CO</td>
<td>13ppm (1.6 mbar)</td>
<td>0.06-1 ppm (0.001-0.1 mbar)</td>
<td></td>
</tr>
<tr>
<td>He</td>
<td>12 ppm (1.1 mbar)</td>
<td>5 ppm (0.5 mbar)</td>
<td></td>
</tr>
<tr>
<td>Ne</td>
<td>7 ppm (0.6 mbar)</td>
<td>18 ppm (1.8 mbar)</td>
<td></td>
</tr>
<tr>
<td>³²Ar</td>
<td>30 ppm (2.8 mbar)</td>
<td>32ppm (3.2 mbar)</td>
<td></td>
</tr>
<tr>
<td>⁴⁰Ar</td>
<td>40 ppm (3.9 mbar)</td>
<td>0.93% (9.3 mbar)</td>
<td></td>
</tr>
</tbody>
</table>

Earth has hidden (non-gaseous form)

- ~60 bar worth of CO₂
  - in carbonate rocks (limestone)
  - and in oceans (bicarbonate)
  - and in life.

- ~100 bar worth of H₂O
  - all as liquid & solid (oceans & ice caps)

Because of its high temps, it's doubtful Venus has much "hidden".
- Venus & Earth not so different in terms of CO$_2$ content, it's just not all in the atmosphere on Earth.

- Earth has oceans, and appears to have had them from an early time.
  - CO$_2$ dissolves in water
  - CO$_2$ in water precipitates out as carbonates in sediments (limestone)
    - Happens fast with life (phytoplanktons)
    - But still happens w/o life
  - Earth's CO$_2$ abundance got put back into rocks.

- Venus has almost no water, compared to Earth's huge abundance of it.
- What happened to Venus' water? (or did it ever have any?)
- To answer that question, we have to step back and think about where atmospheres come from in the first place.
First, let's list possible sources of planetary atmospheres:

- The planetary nebula - primarily H₂, He, ...
  - Difficult to hold much of this especially in inner solar system; OK for outer solar system where it was cooler & planets grew bigger.

- Gases released from interior during accretion
  - Plausible, as planetesimals do have some volatiles which would be released upon accretional heating.
    (Potential Energy $\rightarrow$ Kinetic Energy)

- Gases released from interior after accretion
  - Degassing (Outgassing)
  - Plausible since volcanoes give off: CO₂, H₂O, N₂, SO₂, ...
  - Earth & Venus have volcanic action (though different)
    Earth - plate tectonics
    Venus - expansion/contraction volcanism
  - ^{40}Ar comes from radioactive decay of ^{40}K

- Gases released by later impacts of volatile-rich planetesimals (comets from outer solar system)
  - We know comets have H₂O, CO₂, ...
  - We know there was a "Late Heavy Bombardment" in the 3.6 - 4.0 Billion Years ago timeframe (accretion was 4.5 - 4.6 Bya)
  - Idea was popular ~10 yrs ago, but has less favor now (isotope ratios)
• Sublimation of surface volatiles
  - i.e. vapor pressure
  - certainly a source, but not the primary one of Venus, Earth, & Mars

• Sputtering/micrometeorite Impacts
  - small impacts (dust, solar wind) kick up stuff
  - Source of Mercury & Moon atmospheres
  - Not a significant source for Venus, Earth, & Mars

- Obviously not all planets’ atmospheres can be explained by any one source
- Not all atmospheres can be explained by combinations either.

- Next, let’s list possible loss processes of gases from planetary atmospheres:

• Thermal (Jean’s) Escape from top of atmosphere
  - Recall above exobase atoms & molecules are in “ballistic” orbits, with few collisions
  - Escape can occur if kinetic energy velocity exceeds gravitational escape velocity.
Thermal Equilibrium gives rise to "Maxwellian" distribution of velocities.

- Peak of distribution = most probable velocity
  where \( \sqrt{3} m v_m^2 = \frac{1}{2} kT \)
  \( v_m = \sqrt{\frac{3 kT}{m}} \)
- Tail is \( \sim \) exponential.

If \( v > v_{esc} \) (there will be some) then stuff going up will escape.

\[ \frac{1}{2} m v_{esc}^2 = \frac{m M G}{r} \]
\[ v_{esc} = \sqrt{\frac{2 M G}{r}} \]

\( v_{esc} \) depends on Mass of planet and distance from planet.

- \( v_{esc} \) (Earth) = 11.2 km/sec
- \( v_{esc} \) (Venus) = 10.7 km/sec

Thermal or Jean's escape is highly dependent on temp. and what molecule/atom you are talking about.