Lecture 13: Venus, Earth, and Mars

Astro 202
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Spring 2008

But first...

- Paper 4 is posted online
- Paper 4 is due at beginning of class on Mar. 13
  - No extensions over Spring Break!
- Keep up with reading through PBD 13
- Three special readings for the Terrestrial Climate Change lecture next Tuesday are also now posted online...

Comparing Venus, Earth, & Mars

✓ Surface and Atmosphere of Venus
  ✓ Radar mapping results
  ✓ Greenhouse gone wild!
✓ Surface and Atmosphere of Mars
  ✓ The view from orbiters, landers, and rovers
  ✓ Once Earthlike, now not... How?
✓ Lessons for our home world...

Venus and Earth:
So Similar...

<table>
<thead>
<tr>
<th>Property</th>
<th>Earth</th>
<th>Venus</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter (km)</td>
<td>12,756</td>
<td>12,104</td>
</tr>
<tr>
<td>Mass (kg)</td>
<td>6.0x10^24</td>
<td>4.9x10^24</td>
</tr>
<tr>
<td>Density (g/cm^3)</td>
<td>5.52</td>
<td>5.25</td>
</tr>
<tr>
<td>Gravity (m/sec^2)</td>
<td>9.8</td>
<td>8.9</td>
</tr>
<tr>
<td>Period (years)</td>
<td>1.0</td>
<td>0.62</td>
</tr>
<tr>
<td>Surface Composition</td>
<td>basalt</td>
<td>basalt</td>
</tr>
</tbody>
</table>
Yet So different...

<table>
<thead>
<tr>
<th>Property</th>
<th>Earth</th>
<th>Venus</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spin Period (days)</td>
<td>1.0</td>
<td>-243.0</td>
</tr>
<tr>
<td>Tilt of Axis</td>
<td>23.5°</td>
<td>177.4°</td>
</tr>
<tr>
<td>Surface Temperature</td>
<td>~ 25°C</td>
<td>~ 480°C</td>
</tr>
<tr>
<td>Surface Pressure (bars)</td>
<td>1</td>
<td>90</td>
</tr>
<tr>
<td>Atmospheric Comp.</td>
<td>N₂,O₂, Ar, CO₂, N₂, ...</td>
<td></td>
</tr>
</tbody>
</table>

Venus: Seeing is Believing...

- Recall: The surface of Venus is obscured from view at visible to infrared wavelengths by a thick layer of clouds.
- But light at radio wavelengths (~1 mm to ~1 m) penetrates the clouds.
- Radar (an acronym for RAdio Detection And Ranging) is used to study the surface of Venus remotely.
- Radar mapping of Venus done by the Soviet Venera and U.S. Magellan space missions.

“Radar Measures Roughness”

- Smooth surfaces scatter radio waves back to the transmitter like a mirror (specular).
- Rough surfaces scatter radio waves in all directions (diffuse).

In Venus pictures: Bright = Rough, Dark = Smooth

Radar image of Venus
The Magellan Mission

- Named after the 16th century Portuguese explorer whose expedition first circumnavigated the Earth
- Launched from the Space Shuttle in May 1989
  - Covered 98% of Venus' surface with a resolution of ~1 km
  - Measured surface topography to ~100 m vertical resolution
  - Measured global gravity field to high accuracy
  - Provided data for insights on surface geologic processes and the nature of the planet's interior

Very Simple Spacecraft!

- Essentially just a large satellite dish with a transmitter and receiver
- Used spare parts from Voyager and other Earth and planetary missions
- Cost: about $650 million
  [compare: B1 Bomber: $200 million; B2 Bomber: $2.2 billion]

Geology of Venus: Magellan Results

- Abundant evidence of past volcanism
- Nearly 1000 impact craters > 1 km discovered
  - Crater density implies ~500 million year age
  - Some small areas may be much more recent
  - No "ancient" surface preserved
- Abundant evidence of tectonism
  - But no clear evidence of plate tectonics like Earth
- Some evidence for erosion
  - Dunes, wind streaks, lava channels

Venus Topography: Most of the surface is at the same narrow range of elevations (vast lava plains)
### Venus Global Topography

- Magellan data show vast expanses of low-lying lava plains
- Two large "continents":
  - Aphrodite (Africa-sized)
  - Ishtar (Australia-sized): highest point 1 km (Maxwell Montes)

### Volcanism on Venus

- Hundreds of thousands of volcanoes have been discovered on Venus!
- Volcanism is widespread and planetwide
- Vast lava plains, like the lunar “mare”?
- Many individual cones and mountains
- Also: evidence for *subsurface* volcanism

### Impact Craters on Venus

- Nearly 1000 craters > 1 km diameter have been discovered in Magellan images
  - Very few craters smaller than 10 km
  - Impactors smaller than 1 km in size burn up!
  - Craters 10 km to 30 km have irregular shapes
- *Relative Age Dating* (counting craters) indicates a ~uniform surface age of ~500 million years since the last resurfacing
Impact Craters on Venus

- About 1000 found > 1 km
- Pretty evenly distributed around the surface (uniform age?)
- Small regions of lower crater density (younger?)

Tectonism on Venus

- Numerous patterns of ridges and cracks seen in Magellan images
  - Evidence of tectonic forces
  - Probably driven by convection in the interior
- Evidence for mountain belts and rift valleys
- No direct evidence for Earth-like plate tectonics, however
Erosion on Venus

- Evidence for erosion in Magellan images
  - Wind streaks
  - Dunes
  - Long channels carved into the rock
- No water! So erosion must indicate the action of wind and molten lava
  - Surface winds very weak: long timescales
  - Deep, long lava channels: long timescales

Plus oddball landforms!

- Several categories of geologic features found in Magellan images that defy simple categorization!
  - Coronae
  - Arachnoids
  - Mixed terrains
    - Impact, then volcanism, then tectonism... ??
- Sometimes our terrestrial experience doesn’t help
  - Humbling, but to be expected?
View from the Surface

**Venera landers: 1978-1981**
- Confirmed huge surface temperature and pressure
- Enough light gets through the clouds to take pictures
- Surface is flat, platy, maybe layered...?
- Landscape is desolate and totally inhospitable to life

What is Venus made of?

**Soviet Venera 13 and 14 landers measured the chemical composition of the surface**
- Elemental abundances and inferred mineralogy is similar to basalt, a common low-Si volcanic rock found on the Earth, Moon, and Mars
- Presence of distinct "continents" implies the existence of lower-density minerals too
  - Maybe similar to Earth-like granites?
  - We just don’t know...

Critical Question:

Why are the Atmospheres of Earth and Venus so different?

**Answer:**
Earth and Venus have had divergent evolutionary histories

What Makes Venus Hot?

The "Greenhouse" Effect

- Visible light passes through atmosphere.
- Greenhouse gases trap infrared radiation in troposphere, heating lower atmosphere.
- Surface absorbs visible light, emits thermal radiation in infrared.
Recall the Concept (Lecture 12)...

Note: Greenhouses also get warm because they prevent convective cooling by the wind, so the term "greenhouse effect" is somewhat misleading.

Result: Greenhouse Warming

Mars $\Delta T \sim 5^\circ C$
Earth $\Delta T \sim 35^\circ C$
Venus $\Delta T \sim 500^\circ C!!$

How Did Venus Get This Way?

- "Runaway Greenhouse" Model
  - Venus and Earth are assumed to have formed from essentially the same material, with the same initial amounts of $H_2O$, $CO_2$, $N_2$, etc...
  - But divergent evolution occurred because:
    - Venus is closer to the Sun, so $H_2O$ can exist only in vapor (gas) form
    - At Earth's distance, liquid $H_2O$ could form
- Model the atmospheres as time progresses...

Early Earth... Stage 1

- Earth forms from accretion of small planetesimals
- Earth heats up inside
  - Volatiles like $H_2$, $H_2O$, $CH_4$, and $NH_3$ build up in the atmosphere as they outgas from the interior
  - $H$-rich gases mimic the composition of the solar nebula
- $H_2O$ forms liquid oceans
  - $NH_3$ dissolves in water
- Early atmosphere is reducing ($H_2$, $CH_4$ rich)
  - Note: Allows complex organic molecules to exist
Early Earth... Stage 2

- Earth probably differentiated in 500 Myr or less
  - Melting of less dense, oxygen-rich crustal rocks begins to dominate the outgassing (H\textsubscript{2}O, CO\textsubscript{2}, SO\textsubscript{2}, N\textsubscript{2}, etc.)
  - Rates and abundances can be measured from volcanoes like Kilauea (Hawaii) today
- CO\textsubscript{2}, SO\textsubscript{2} dissolve in the oceans (e.g., limestone)
  - Estimated to be equivalent of ~100 bars of CO\textsubscript{2} stored in rocks!
- Atmosphere ends up being mostly N\textsubscript{2}
- O\textsubscript{2} slowly builds up over time from breakdown of H\textsubscript{2}O and (eventually) presence of life...

Early Venus...

- Venus' original volatiles probably similar to Earth's
  - H\textsubscript{2}, H\textsubscript{2}O, CH\textsubscript{4}, and NH\textsubscript{3} build up in the atmosphere
- BUT: Temperature too hot for liquid water!
- Venus differentiates, oxygen-rich gases released
  - H\textsubscript{2}O, CO\textsubscript{2}, SO\textsubscript{2}, N\textsubscript{2}, etc.
  - No ocean to dissolve the CO\textsubscript{2} or SO\textsubscript{2}; they build up
- H\textsubscript{2}O, other gases dissociated by UV light
  - 2H\textsubscript{2}O + UV photon $\rightarrow$ O\textsubscript{2} + 2 H\textsubscript{2}
  - H\textsubscript{2} (very light) escapes to space
  - O\textsubscript{2} oxidizes surface rocks (efficient at high T)

Present Venus...

- Result is that large amounts of CO\textsubscript{2} and lesser amounts of N\textsubscript{2} and SO\textsubscript{2} remain
  - 90 bars of CO\textsubscript{2} (close to Earth's equivalent)
- H-bearing gases oxidized by free O\textsubscript{2}
  - With SO\textsubscript{2} they form sulfuric acid (H\textsubscript{2}SO\textsubscript{4})
- Surface oxidized (rusted; reddened) by free O\textsubscript{2}
- CO\textsubscript{2} traps outgoing heat radiation as it builds up, causing the greenhouse effect to "run away" until it reaches equilibrium

If this model is correct, then...

- Venus should have "lost" an ocean's worth of water during its history!
  - Some evidence provided by enhanced abundance of "heavy water" (D\textsubscript{2}O) on Venus today (D\textsubscript{2}O escapes slower than H\textsubscript{2}O)
- But still controversial
- Need better measurements of atmospheric and surface composition to test this model
But also consider...

✓ Slow, backwards spin of Venus might indicate some catastrophic early event
  - Venus hit by giant impact? Controversial.
  - Venus had a moon that spiraled in? Hmm...
  - Whatever the cause, probably were large implications
✓ Is the Earth headed in the same direction?
  - Short-term: global warming and CO$_2$ buildup
  - Long-term: Sun becomes a red giant, Earth's oceans evaporate, CO$_2$ in rocks is released (in ~5 billion years)

Now let's consider Mars...

- Average Distance from Sun: 227,900,000 km (a=1.52 AU)
- Orbital period: 687 days
- Period of Spin around axis: 24 hours, 37 minutes (= 1 Sol)
- Tilt of Martian spin axis: 25.2° (Mars has seasons)
- Mass: 6.7x10$^{23}$ kg = 0.11 $M_E$; Radius: 3397 km = 0.53 $R_E$
  - Surface area of Mars = Land area of Earth's continents
  - Density = 3.9 g/cm$^3$ (little metal; some ice? (Earth: 5.5))
  - Surface Gravity = 3.7 m/sec$^2$ (38% of Earth's)
  - Thin CO$_2$-rich atmosphere; Surface pressure ~1% Earth's
  - Average Surface Temperature: -60°C (-76°F); $\Delta T$ ~100°C
  - Complex surface geologic processes at work...

Telescopic Observations

✓ Mars usually has a small apparent angular diameter in telescopes: < 10 arcsec
✓ Every 26 months or so, Mars' apparent angular size increases for a few months and astronomers can observe surface details

And oh what details they have observed!

Percival Lowell and the "canals" of Mars

Limitations on Resolution

✓ Atmospheric turbulence (seeing) limits the resolution of features on Mars to a few hundred km (~size of Arizona) from ground based telescopes
✓ Hubble Space Telescope can get to about 20 km

Space Missions

20 robotic space missions have either flown by, orbited, or landed successfully on Mars (out of ~ 40 attempts)

<table>
<thead>
<tr>
<th>Mission Name</th>
<th>Dates</th>
<th>Goals and Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mariner 4</td>
<td>1965</td>
<td>Mars flyby; photography</td>
</tr>
<tr>
<td>Mariner 6 &amp; 7</td>
<td>1969</td>
<td>Mars flybys; photography, spectroscopy</td>
</tr>
<tr>
<td>Mariner 9</td>
<td>1971</td>
<td>Mars orbiter; photography</td>
</tr>
<tr>
<td>Mars 2 &amp; 3</td>
<td>1971</td>
<td>Mars orbiters and lander (no data); photography</td>
</tr>
<tr>
<td>Mars 4 &amp; 5</td>
<td>1974</td>
<td>Mars orbiter; photography, polarimetry</td>
</tr>
<tr>
<td>Viking 1 &amp; 2</td>
<td>1976-1982</td>
<td>2 orbiters and 2 landers; imaging, soil analyses</td>
</tr>
<tr>
<td>Phobos 2</td>
<td>1989</td>
<td>Mars orbiter; CCD imaging, imaging spectroscopy</td>
</tr>
<tr>
<td>Mars Pathfinder</td>
<td>1997</td>
<td>Mars lander &amp; rover, CCD imaging, geochemistry</td>
</tr>
<tr>
<td>Mars Global Surveyor</td>
<td>1996-2006</td>
<td>Mars orbiter; images, spectra, topography &amp; magnetic fields</td>
</tr>
<tr>
<td>Mars Odyssey</td>
<td>2001-</td>
<td>Mars orbiter: spectroscopy &amp; IR imaging</td>
</tr>
<tr>
<td>Mars Express</td>
<td>2004-</td>
<td>Mars orbiter: spectroscopy, imaging, radar</td>
</tr>
<tr>
<td>Mars Exploration Rovers</td>
<td>2004-</td>
<td>Spirit &amp; Opportunity; geology, mineralogy during long traverses</td>
</tr>
<tr>
<td>Mars Reconnaissance Orbiter</td>
<td>2006-</td>
<td>Mars orbiter: spectroscopy, imaging, radar</td>
</tr>
<tr>
<td>Phoenix</td>
<td>2008 (?)</td>
<td>Mars north polar lander; trenching, ice chemistry, geology</td>
</tr>
<tr>
<td>Mars Science Laboratory</td>
<td>2009- (%)</td>
<td>Long-range Mars rover; geology, organic chemistry</td>
</tr>
</tbody>
</table>

The Atmosphere of Mars

Composition determined by spectroscopy from ground based telescopes and direct sampling by surface landers

<table>
<thead>
<tr>
<th>Gas</th>
<th>Mars (%)</th>
<th>Earth (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon Dioxide (CO₂)</td>
<td>95.3%</td>
<td>0.03%</td>
</tr>
<tr>
<td>Nitrogen (N₂)</td>
<td>2.7</td>
<td>78.1</td>
</tr>
<tr>
<td>Argon (Ar)</td>
<td>1.6</td>
<td>0.93</td>
</tr>
<tr>
<td>Oxygen (O₂)</td>
<td>0.13</td>
<td>21.0</td>
</tr>
<tr>
<td>Water (H₂O)</td>
<td>0.03</td>
<td>~2</td>
</tr>
</tbody>
</table>

Mars Has Seasons!

Because the Martian orbit is eccentric (e = 0.09), the seasons have unequal lengths

- Southern summer (northern winter)
  - Short: 154 Martian days
  - Occurs near perihelion: a(1-e) = 1.52(1-0.09) = 1.38 AU
- Northern summer (southern winter)
  - Long: 178 Martian days
  - Occurs near aphelion: a(1+e) = 1.66 AU

Solar heat input ratio = (1.66 / 1.38)^2 = 1.45
- Almost 50% more heat input when closer to the Sun!
- This has a strong effect on the weather patterns!
Dust Storms!

✓ Occur primarily during times of strongest solar heating (southern summer)
✓ Clouds of micron-sized (smoke-sized) reddish dust lifted and transported by the winds
  – Wind speeds in excess of 100-150 mph common!
  – BUT: not much force, since pressure ≤ 10 millibars
✓ Dust clouds have a strong influence on the weather, since they strongly absorb sunlight and prevent much of it from reaching the surface
  – Important climate implications for Mars and Earth

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Global dust storm (1971)
- Surface features completely wiped out from view!
- Last major global dust storms: 1973, 2001
- Smaller storms seen by the Viking and Pathfinder landers and by the rovers in 2007

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Large Martian dust storm in summer 2007...

Mars S. Hem. Dust Storm
June 20 to July 18, 2007
MRO/MARCI
(MSSS)
Mars has Polar Caps

- Mars winters are so cold (-120°C or about -200°F) that CO₂ condenses out onto the surface!
- 25% of the atmosphere "snows out" onto the ground!
- Analogy for Earth: at -320°F, N₂ would snow out
- A seasonal CO₂ polar cap a few meters thick forms
- In spring, the CO₂ sublimes back to the atmosphere
- There are permanent polar caps underneath
  - Composed primarily of water ice! (only minor CO₂ ice)
  - May be 1-2 km thick! (depth uncertain...)

North Polar Cap
Size ~ 1000 km

South Polar Cap
Size ~ 350 km

Stored in the polar caps are layers of bright and dark deposits
Evidence for climate change on Mars???

Geology of Mars

- Mars is a geologically exciting place!
  - Abundant evidence of past volcanism
  - Abundant evidence of past tectonism
  - Abundant evidence of past impact cratering
  - Abundant evidence of past and current erosion
- Our knowledge comes from orbital imaging, augmented by close-up studies at 5 specific landing sites

The View from the Surface

- Five missions have successfully returned images and other data from the surface of Mars
  - Viking Lander 1
    - 600 kg landed mass, powered by two 238Pu RTGs
    - Landing site: Chryse Planitia (22.7° N, 48.2° W)
    - Operated from July 20, 1976 to November 13, 1982
  - Viking Lander 2
    - Landing site: Utopia Planitia (48.3° N, 226.0° W)
    - Operated from September 3, 1976 to April 11, 1980
  - Mars Pathfinder
    - 360 kg landed mass (Rover = 16 kg), solar panels
    - Landing site: Ares Valles (19.3° N, 33.6° W)
    - Operated from July 4, 1997 to September 27, 1997
The View from the Surface

- Mars Exploration Rover *Spirit*
  - 180 kg landed mass, powered by solar panels
  - Landing site: Gusev crater (14.6° S, 175.5° E)
- Mars Exploration Rover *Opportunity*
  - Landing site: Meridiani Planum (2.0° S, 354.5° E)
- Next: *Phoenix* Mars polar lander
  - 350 kg landed mass, powered by solar panels
  - Landing site: high northern latitudes (70° N, 250° E)
  - Landing planned for Memorial Day weekend 2008... Stay tuned!

**Viking Landers (1976-1982)**

- Frost at VL2
- Trenches at VL2
- Dunes, boulder at VL1

**Mars Pathfinder (1997)**

- "Hold still, Larry, it's taking another picture..."
Volcanism on Mars

- Two large volcanic provinces on Mars
  - Tharsis: An enormous 10 km bulge in the crust
  - Elysium: Smaller, localized elevated region
- Relative age dating from crater counts indicates that these volcanoes are relatively young (< 100 million years?)
- Mars may be volcanically active today, though we have not seen direct evidence...

Mars Tectonism

- Spectacular rifting of the Martian crust has occurred
  - Triggered by bulging of Tharsis?
  - Largest rift: Valles Marineris canyon system
    - 5000 km long, 100 km wide, 7 km deep (~ 5 miles deep!!)
- No signs of compression (e.g., no folded or uplifted mountains)
- Speculations, but no conclusive evidence for Earth-like plate tectonics on Mars
Impact Cratering on Mars

- Thousands of impact craters on Mars
  - Sizes range from a few meters to 1500 km

- Many more craters in the south (older)
- But even "young" areas have many craters

Age of the surface based on craters

- Craters used to develop the stratigraphy of the Martian surface
- Absolute ages have large uncertainties
- Most recent volcanism: from 0.1 to 2.0 billion years ago?
Mars Erosional Features

- Evidence for substantial movement of materials on Mars
  - Gravity
    - Landslides, Slumps, Ejecta Blankets
  - Wind
    - Dunes, Streaks, Dust Storms, Dust Devils
  - Water
    - Outflow channels, Runoff channels (valley networks)
  - Ice
    - Polar ice caps today, glaciers elsewhere long ago?

Topography of Mars

- Enormous range of elevations on Mars!
- Highest high: +25 km (Olympus Mons)
- Lowest low: -5 km (Hellas Basin)
- Factor of 20 in atmospheric pressure!
Mars Climate

Today

✓ Cold
  – Average temperature: -60°C
✓ Bone Dry
  – Equivalent to only a few microns of liquid H₂O
✓ Lifeless, as far as we can tell
  – Viking was sensitive to ppb levels of organics
  – No ozone layer: Sun's UV gets to surface

Mars ~3 billion years ago?

✓ Warm
  – Thicker atmosphere, more greenhouse effect
✓ Wet
  – More water, in liquid form?
✓ Hospitable?
  – Same ingredients for life as early Earth?

The Climate of Mars has Changed Drastically

This is a THEORY: What's the evidence?

Evidence for Mars Climate Change

✓ Valley Networks
  (a.k.a. "Runoff Channels")
✓ Heavy erosion of old craters
  (degraded rims, no ejecta blankets)
✓ Presence of surface and subsurface ice
  (abundant "stored" water?)

Mars had a Magnetic Field...

✓ Mars has no global magnetic field today
✓ If Mars has (or had) a molten iron core like the Earth, then why doesn't it have a magnetic field?

• Data from the Mars Global Surveyor mission reveal regions of the surface that appear to retain a remanent magnetism
• Was the core molten long ago?
• Consistent with early volcanism
• But the data still sparse and somewhat controversial...

Acuña et al., 2008
Martian Channels

- Outflow channels
  - Hundreds of km long, tens of km wide
  - Contain clear signs of fluid (water) erosion
  - Contain evidence of catastrophic flooding
  - Source areas: collapsed terrain
  - Formed by rapid melting of subsurface ice?
    * How? Volcanism? Impacts?
- OLD
  - 2.5-3.5 b.y.?
  - Drainage: S to N

Martian Channels

- Valley Networks
  - a.k.a "runoff channels"
  - Only tens of km long, a few km wide
  - Little/no evidence of fluid erosion
  - Caused by sapping (undermining)?
- VERY OLD
  - 3.5 b.y. + ?
  - Only found in the ancient S. highlands

Polar Layered Deposits

- Evidence for cyclical climate change on Mars
- Many years of warmer, dustier conditions
  - Accumulation of dark, dusty airfall layers in the ice
- Then, many years of colder conditions
  - Less dust accumulation, brighter, icier layers

From the thickness of the layers (tens of meters) and an assumption about the rate of dust accumulation, we can estimate how long it took to form each layer: 10^5 to 10^6 years

- Darker layer (more dust, less ice)
- Brighter layer (less dust, more ice) etc...

N. Polar layers in Viking image
Trough is about 500 m deep
Each layer is about 50 m thick
Layers about 10 m thick could be detected from early orbiter images...
Layers only a few meters thick can be detected from newer high-resolution orbital images...
**Liquid Water on Mars?**

- Can liquid water exist on Mars today?
- **Probably not**, according to the *phase diagram* of water
  - *Phase* of water (solid, liquid, or vapor) depends on Pressure & Temperature
  - Important concept, but not well described/discussed in the textbook...

  If the temperature on Mars is not > 273 K and the pressure is not > 6.1 mbar, no liquid water is possible.

**Digression: Snowballs on Mars?**

- Q: Could you have a snowball fight on Mars?
- A: Sadly, probably not...

  - Compressing snow on Earth turns some of the snow into liquid water (line ABC), which "cements" the snowball...
  - On Mars, the phase remains solid, whether H₂O or CO₂ (line DEF)
  - This also means:
    - no skiing/snowboarding on Mars
    - no ice skating on Mars
      :(

**Climate Change on Earth and Mars**

- We know that significant and *cyclic* climate changes have occurred on Earth (e.g., ice ages)
- These climate changes are thought to be caused by variations in Earth's orbital parameters
  - Earth's polar axis precession: ~26,000 year timescale
  - Changes in Earth's tilt: ~ 41,000 year timescale
  - Changes in Earth's eccentricity: ~100,000 year timescale
- The same kinds of orbital variations occur for Mars: Cyclic climate changes there too?
Summary: Venus

 ✓ Radar has been used to penetrate the clouds of Venus and discover the underlying geology of the planet
   - Radard measures roughness (bright=rough; dark=smooth)
 ✓ Abundant evidence for volcanism, tectonism, impact, and erosion on Venus!
 ✓ Entire planet appears to have been resurfaced, possibly by volcanoes, ~500 million years ago
 ✓ Surface composition appears similar to Earth's volcanic rocks

Summary: Venus & Earth

 ✓ Venus and Earth similar in bulk properties, but with very different atmospheres
 ✓ The Greenhouse Effect is responsible for the high surface temperature of Venus
 ✓ Earth and Venus have had divergent histories
   - Similar starting compositions
   - But liquid water on Earth has removed most of the greenhouse gas CO₂ from our atmosphere
   - With no oceans, CO₂ has built up and caused the greenhouse to run wild on Venus

Summary: Mars

 ✓ Mars is a small rocky planet with a thin atmosphere
 ✓ Telescopic observations reveal changing surface features (polar caps, dust storms, dark features)
 ✓ The Martian atmosphere is almost entirely CO₂, and the surface pressure is only ~1% of Earth's
 ✓ Mars has seasons, and the planet's eccentric orbit results in big differences in seasonal weather
 ✓ Mars has been extensively studied by spacecraft

Summary: Mars & Earth

 ✓ There is very good evidence that the Martian climate was very different 3-4 billion years ago than today
   - Valley networks, suggesting subsurface ice or water
   - Outflow channels, indicating huge floods
   - Polar layered deposits, suggesting cyclic changes
 ✓ Mars climate changes may be caused by the same astronomical orbit variations that are thought to cause major changes in Earth's climate
 ✓ Amazingly, liquid water may be stable near the Martian surface today, despite contrary predictions
 ✓ Major implications for life on Mars... (Part 5 of class...)
Next Time...

Climates of the Giant Planets
Guest lecturer:
Prof. Peter Gierasch

Reading: PBD 14, Review NSS 15