This lecture compares and contrasts the properties and evolution of the 5 main terrestrial bodies.

The small terrestrial planets have old surfaces and cold interiors.

The large terrestrial planets have young surfaces and hot interiors.

All terrestrial planets probably started with substantial atmospheres, but subsequent evolution was different.

Atmosphere evolution is driven by a combination of the greenhouse effect, the presence or absence of liquid water, and the gravity of the planet.

The Terrestrial Planets

Large Bodies:
- Earth (1 Re, 1 Me)
- Venus (0.95 Re, 0.82 Me)

Small Bodies:
- Mars (0.53 Re, 0.11 Me)
- Mercury (0.38 Re, 0.055 Me)
- Moon (0.27 Re, 0.012 Me)
The evolution of planetary surfaces is driven by impact cratering, volcanism, and tectonism. Impact cratering is only important during the first Gyr of the Solar System.

Volcanism & Tectonism are driven by the internal structure of the planets. Is the interior hot enough to for tectonics or volcanism?

The surfaces of the small terrestrial planets were shaped primarily by impacts and early volcanism. Mars, Mercury & the Moon: Old, heavily cratered surfaces >3 Gyr old Single, continuous crust (no plates) Vertical Tectonism (stationary upwelling)

Crustal Shaping:
Primary crust: shaped by impacts
Secondary crust: shaped by volcanism

Lava plains (Maria) on the Moon
Lava plains and volcanic vents on Mercury
Hot-spot volcanoes on Mars

Evidence of past volcanism on Mercury and Mars

Volcanic vents on Mercury [MESSENGER] Hot Spot Shield Volcanoes on Mars [NASA MGS]
The surfaces of the large terrestrial planets are young, with active tertiary crusts.

Earth's surface is ~100 Myr old
Venus' surface is ~500 Myr old

**Earth:** plate tectonics & lateral recycling:
- subduction, sea-floor spreading &
- Up-thrust constantly rebuild the crust.

**Venus:** one-plate crust & vertical recycling:
- volcanoes over mantle upwelling,
- compression over mantle down-welling.

**Vertical recycling tectonism on Venus**

Pancake Domes
Magma upwelling
pushes up the crust

Corona
Magma down-welling
collapsing the crust

**Internal heating & subsequent cooling drives the evolution of planetary interiors.**

**First Stage:** Differentiation (heat of formation)
- Dense molten metals sink into the core.
- Lighter silicate rocks float to the crust.

**Second stage:** Volcanism
- Mantle still molten due to internal heating by radioactive decay and heavy impacts.
- Magmas rise to the surface as volcanoes
The cooling time of a terrestrial planet scales as the size of the planet.

Start with the total internal thermal energy:

$$Total\ Energy = const \times R^3 T$$

Cool by radiation losses from the surface:

$$Energy\ Loss\ Rate = 4\pi R^2 \sigma T^4$$

The Cooling Time is the ratio of the total energy to the loss rate:

$$Cooling\ Time = const \times \frac{R}{T^3}$$

*Hotter bodies cool faster than cooler bodies.*  
*Larger bodies cool more slowly than small bodies.*

The interiors of the small terrestrial planets cooled rapidly and have mostly solidified.

A solid mantle ends tectonic activity.   
All have thick, cool, rigid crusts.

Mercury has signs of ancient volcanic vents.  
Mars has large, extinct shield volcanoes.

The large terrestrial planets cool more slowly and are still hot.

Kept hotter longer by energy released from the decay of radioactive elements.

Convective motions in molten mantles drive tectonism and gives them active tertiary crusts.
The atmospheres of all of the terrestrial planets started out roughly similarly. During formation, the terrestrial planets were molten from impacts with planetesimals:

- Fewer volatiles close to the proto Sun (too hot)
- Get more volatiles moving out into the Solar System (cooler)

Primordial Atmosphere Formation:

- Outgassing from volcanoes
- Comet impacts delivering frozen volatiles
- Primary gases are CO$_2$, H$_2$O, & N$_2$

All started with CO$_2$, N$_2$, & H$_2$O atmospheres.

The evolution of Terrestrial Planet atmospheres is driven by three primary effects:

- **Greenhouse Effect:**
  - Solar heating & atmospheric cooling balance
  - Helps determine if H$_2$O is liquid, ice, or vapor

- **Planetary Gravity:**
  - Determines a planet's ability to retain hot atoms & molecules.

- **Chemistry of CO$_2$ and H$_2$O:**
  - CO$_2$ is easily dissolved in liquid H$_2$O
  - Help determine the atmospheric CO$_2$ content, and its contribution to the Greenhouse Effect.

The Greenhouse Effect makes the temperature warmer than if there was no atmosphere.

<table>
<thead>
<tr>
<th>Without Atmosphere</th>
<th>With Atmosphere</th>
<th>Water</th>
</tr>
</thead>
<tbody>
<tr>
<td>Earth 255K</td>
<td>287K</td>
<td>Liquid</td>
</tr>
<tr>
<td>Venus 280 K</td>
<td>750 K</td>
<td>Vapor</td>
</tr>
<tr>
<td>Mars 214 K</td>
<td>220 K</td>
<td>Ice</td>
</tr>
</tbody>
</table>

*But: It can be an unstable process...*
Runaway Greenhouse Effect

Increase Solar Radiation

Increase Surface Temperature

Higher Air Temperature: Increase evaporation
Warmer air holds more water vapor

Oceans Evaporate
Carbonate Rocks break down
CO₂ released

Greenhouse Effect Runs Away

Positive Feedback Loop

More Water Vapor: Greater IR absorption
Stronger Greenhouse Effect
Higher Air Temperature

The ability of a planet to retain atmospheric gases depends on its mass and temperature.

Mercury is too hot for liquid water, and its gravity too weak to retain an atmosphere.

Lack of liquid water shutdown CO₂ and H₂O chemistry resulting in a Runaway Greenhouse Effect

Surface gravity was too weak to hold onto its hot atmosphere, so it lost all of its volatiles after ~1 Gyr

Result: Mercury has no atmosphere today
Venus’ Atmosphere was also too hot for liquid water, but large enough to retain its atmosphere. May have had early oceans that evaporated resulting in a Runaway Greenhouse Effect. Gravity is strong enough to retain its atmosphere, so ended up with a hot, heavy CO$_2$ and N$_2$ atmosphere. All of the H$_2$O lost to UV photolysis H$_2$ escaped and the O reacted with other gasses. Result: **Venus has a bone dry, hot, heavy CO$_2$ atmosphere**

Earth’s Atmosphere was warm enough for abundant liquid water, and large enough to keep it. The H$_2$O condensed into massive, deep oceans and setup a water cycle of evaporation and precipitation. CO$_2$ chemistry in liquid water results in most of the CO$_2$ locked up in the oceans & carbonaceous rocks. Plants thrive in liquid water, converting CO$_2$ into O$_2$. A mild Greenhouse Effect keeps water liquid. Result: **Earth has a warm, moist N$_2$ & O$_2$ atmosphere**

Mars’ Atmosphere may have been warm enough for liquid water during first Gyr, but too weak to keep it. Some CO$_2$ locked into carbonaceous rocks?? Evidence of past water from the Mars Rovers. As Mars cooled, the H$_2$O froze out (most may already have been frozen into saturated rocks). Remaining CO$_2$ and N$_2$ escapes Mars’ weak gravity, aided by the solar wind because of a weak magnetic field. Result: **Mars has a cold, dry, thin CO$_2$ atmosphere today, but might have been hospitable in the past.**
The present-day terrestrial planet atmospheres are different outcomes of atmosphere evolution from similar starting points.

<table>
<thead>
<tr>
<th></th>
<th>Earth</th>
<th>Venus</th>
<th>Mars</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂</td>
<td>0.035%</td>
<td>96%</td>
<td>95%</td>
</tr>
<tr>
<td>N₂</td>
<td>77%</td>
<td>3.5%</td>
<td>2.7%</td>
</tr>
<tr>
<td>H₂O</td>
<td>1%</td>
<td>0.01%</td>
<td>0.007%</td>
</tr>
<tr>
<td>Ar</td>
<td>0.93%</td>
<td>0.007%</td>
<td>1.6%</td>
</tr>
<tr>
<td>O₂</td>
<td>21%</td>
<td>trace</td>
<td>trace</td>
</tr>
<tr>
<td>Temp</td>
<td>287K</td>
<td>750K</td>
<td>220K</td>
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Habitable Inhospitable Today