10. Terrestrial Planets: Evolution
Internal Structure

- **Inner core (solid)**: Iron/Nickel/Cobalt
- **Outer core (liquid)**: Fe/Ni/Co & O/S?
- **Lower mantle (plastic)**: Rock (Si/Mg/O/Al/...)

Earth's Interior & Plate Tectonics
Evolutionary History: Deep Similarities

Terrestrial planets differentiated: high-density metal sank downward, while low-density rock floated upward.

To differentiate, the planets must have melted completely.
Evolutionary History

How did this variety arise?

Mercury: Many Craters, Smooth Plains, High Cliffs

Venus: Volcanos, “Continents,” Few Craters

Earth: Volcanos, Continents!, Oceans

Earth’s moon: Many Craters, Highlands, Smooth Plains

Mars: Volcanos, Some Craters, Riverbeds?
Evolutionary History: Size Makes a Difference

Large planets stay hot — \textit{why}?

More \textit{volume} per unit of \textit{surface}.

More \textit{heat outflow} through unit of surface.
Evolutionary History: Cooling Off

Smaller planets have cooled more, and therefore are solid to greater depths.

Near-solid region is called the **lithosphere**.
The Age of the Solar System

Radioactive elements decay into stable ones; e.g.,

\[ ^{40}\text{K} \rightarrow ^{40}\text{Ar} + e^+ \]

(Potassium-40) (Argon-40) (positron)

The rate of decay is fixed by the element’s **half-life**, the time for 50% to decay; for \(^{40}\text{K}\), this time is 1.25 Gyr (1 Gyr = 1 billion years).

Rocks contain no \(^{40}\text{Ar}\) when they form; by measuring the ratio of \(^{40}\text{Ar}\) to \(^{40}\text{K}\), the rock’s age can be found.
The Age of the Solar System: Dating Rocks

- The oldest Earth rocks are \approx 3.8 \text{ Gyr old}.

- The oldest Moon rocks are \approx 4.4 \text{ Gyr old}.

- The oldest meteorites are 4.55 \text{ Gyr old}; this is how long ago minerals \textit{started condensing} in the disk.
The Moon & Mercury

Both exhibit craters and smooth plains.
Formation of the Moon by Giant Impact

Mars-sized planet (Thea) hits Earth about 4.5 Gyr ago.

Moon forms from debris:

This explains why Moon is poor in metals and volatiles.
Impact Cratering

• occurs on *any* body with a solid surface

• impact vaporizes projectile and comparable mass of target

• expanding vapor blasts material in all directions $\Rightarrow$ circular crater

• craters typically 10 times diameter of projectile
Crater Structure

Small impacts produce simple bowl-shaped craters.

Large impacts produce craters with terraced rims and central peaks.
Impacts: Formation of Lava Plains

4 Gyr ago, a heavily cratered surface.

A giant impact creates a huge crater.

A few 100 Myr later, lava fills crater.

The smooth lava plains of the Moon and Mercury are relics of impacts during “late heavy bombardment”.

Evidence from Moon rocks suggests a peak in cratering rate about 3.8 to 4 Gyr ago.

This would have affected other planets as well.
Mercury (compared to the Moon)

- Fewer craters — more buried by lava floods.
- Giant scarps (cliffs) — tectonic relic of global contraction.
Internal Structure: Mantle Convection

Heat is carried by **convection** — slow circulation of semi-solid rock.
Internal Structure: Convection Simulation

Cold Downwellings  Warm Upwellings
Internal Structure: Convection Simulation

Cold Downwellings  Warm Upwellings

Elapsed time: about 200 Myr.
Mars: Dead or Just Chill?

Normal weather

Global dust storm

Polar cap
Mars: Surface Topography

Evidence for a complex and varied geological history.
Olympus Mons:
hot-spot vulcanism
Valles Marineris: tectonic stresses
Meandering Riverbed?

Crater counts suggest an age of 2 to 3 Gyr.
Evidence for Surface Water in Mars’s Past

Layered *(sedimentary?)* rock in eroded crater (right).

Surface feature resembling sedimentary rock rock (below).
Water on Mars Today

The North and South polar caps contain enough water to make an ocean 15 m deep . . .

More water may exist as permafrost elsewhere on the planet.

Liquid water cannot exist on surface under present conditions — it evaporates due to low pressure.
Water on Ancient Mars

Mars had a more massive CO$_2$-rich atmosphere in the distant past.

The greenhouse effect probably warmed the planet above freezing.
Venus: a Greenhouse Planet

The surface is hidden by thick clouds ... but can be mapped by radar.
Venus: Surface Features

- Shield volcanos
- Lava domes
- Fractured crust (tectonic)
- Impact crater (rare)
- "Corona" (mantle plume)
Venus: Surface Features

- Craters are rare because entire surface was “repaved” 500 — 750 Myr ago.

- Volcanic features are found everywhere, indicating ongoing volcanic activity.

- Tectonic features are unlike those on Earth; no plates!
No Magnetic Field

Thick, dry lithosphere traps heat inside.

Core can’t cool ⇒ no convection.

Heat build-up triggers global “repaving” events.
Impact Craters on Earth

- **Barringer Meteor Crater, Arizona**
  - Age: 49,000 yr
  - Diameter: 1.2 km

- **Manicouagan, Quebec, Canada**
  - Age: 212 Myr
  - Diameter: 70 km
Volcanoes on Earth

Wikipedia: Mount Fuji

Mauna Loa Volcano, Hawaii
Erosion on Earth

Grand Canyon, Arizona
Plate Tectonics

Earth’s crust is a collection of slowly-moving plates.
The plate boundaries are often sites of earthquakes.
Plate Tectonics

Plates *float* on denser mantle material.

*Mantle convection* drives plate motion.

Plates are *formed* at ocean ridges and continental rifts, and *destroyed* in subduction zones.
Plate Tectonics: Age of Sea-Floor

Ages confirm picture of plate formation at ocean ridges.
Plate Tectonics: Continental Drift

150 Million Years Ago

Breakup of Pangaea
### Atmosphere

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<th>Earth</th>
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Secondary Atmospheres

Volcanos release CO\(_2\), H\(_2\)O, etc

Impacts deliver H\(_2\)O, CO, etc
Venus: Atmosphere

Properties:

- 96% CO$_2$; traces of N$_2$, SO$_2$, H$_2$SO$_4$, etc.
- about 90 times mass of Earth’s atmosphere!

Why no H$_2$O? (should be released by volcanos)

- Solar UV radiation breaks up H$_2$O
- Hydrogen is stripped away by solar wind
- Oxygen reacts with surface rocks
Earth: O₂ Cycle

Most O₂ is underground, but exchange between atmosphere and biosphere is the major pathway.

**Biological processes** are the key sources and sinks of O₂:

\[ 6 \text{ CO}_2 + 6 \text{ H}_2\text{O} + \text{ energy} \rightleftharpoons \text{ C}_6\text{H}_12\text{O}_6 + 6 \text{ O}_2 \]

Amount of O₂ is kept fairly constant by competition between sources and sinks.
Earth: CO$_2$ Cycle

Carbon and oxygen *cycle together* over short times.

Over *longer* times, carbon cycles *deep* underground.

This regulates Earth’s climate (very slowly):

- too hot $\Rightarrow$ more CO$_2$ in air $\Rightarrow$ weaker greenhouse
- too cold $\Rightarrow$ less rain $\Rightarrow$ less CO$_2$ in air $\Rightarrow$ stronger greenhouse

Plate tectonics is *necessary* to return buried carbon!
Climate Cycles

Small regular changes in Earth’s orbit and tilt vary the amount of sunlight the northern continents receive.

This triggers an ice-age every $10^5$ yr (roughly).
CO$_2$ and Ice Ages

1. During an ice age, surface ice covers the oceans.
2. CO$_2$ from volcanic outgassing builds up.
3. High CO$_2$ produces rapid warming, ending ice age.
Climate and CO₂

CO₂ concentration and temperature track each other. Now, humans activity is increasing CO₂ concentration.