Lecture 10: Terrestrial planets

Astronomy 111
Terrestrial Planets
Family portrait of the Solar System

Mercury, Venus, Earth, Mars, Jupiter, Saturn, Uranus, Neptune, (Eris, Ceres, Pluto):
My Very Excellent Mother Just Served Us Nine (Extra Cheese Pizzas).
### The Solar System: List of Ingredients

<table>
<thead>
<tr>
<th>Ingredient</th>
<th>Percent of total mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sun</td>
<td>99.8%</td>
</tr>
<tr>
<td>Jupiter</td>
<td>0.1%</td>
</tr>
<tr>
<td>other planets</td>
<td>0.05%</td>
</tr>
<tr>
<td>everything else</td>
<td>0.05%</td>
</tr>
</tbody>
</table>
The Sun dominates the Solar System
Terrestrial planets

Mercury
Venus
Earth
Mars
The terrestrial planets are made primarily of rock and metal.

Mercury, Venus, Earth, & Mars.

The terrestrial planets are: low in mass (< Earth mass) high in density (> 3900 kg/m³).

Water = 1000 kg/m³
Air = 1 kg/m³
Rock = 3000 kg/m³
The terrestrial planets are made primarily of rock and metal.

The mass of a planet is determined by Newton’s version of Kepler’s Third Law.

The average density is mass divided by volume (for a sphere, \( V = \frac{4\pi}{3} r^3 \)).

The density of terrestrial planets is greater than that of rock, reflecting the presence of extremely dense metal cores.
Seismology

How can we study the deep interior of the Earth?

Earthquakes produce seismic waves

We can use these waves to study the interior of Earth
Seismology

Average density of the Earth = 5500 kg/m$^3$

Earth is too dense to be solid rock:
- Basalt = 3300 kg/m$^3$
- Granite = 2700 kg/m$^3$

Parts of Earth must be made of something denser than rock...
Layers of the Earth

From studying seismic events created by earthquakes, we know the Earth has multiple layers:

1) **Crust:**
   - solid rock
   - 5 km thick basalt (ocean floor)
   - 35 km thick granite (continents)

2) **Mantle:**
   - partly solid rock, partly semisolid (plastic)
   - rock 2900 km thick
3) **Outer (liquid) core:**
   - molten iron and nickel
   - 2200 km thick

4) **Inner (solid) core:**
   - solid iron and nickel
   - 1300 km in radius
The Earth is layered because it underwent differentiation when molten.

When young, the Earth was heated by the impact of planetesimals. For a while, the Earth was molten. In a liquid, dense stuff sinks, low-density stuff floats.
Layers of the Earth

When differentiation was complete, Earth cooled and (partly) solidified.

Crust of the ocean floor floats on the mantle “like skin on cocoa”; lower-density continents are the “marshmallows”.

![Layers of the Earth diagram](image)
Plate tectonics

Convection currents in the mantle have broken the Earth’s crust into sections called **plates**.

There are 15 large plates.
Convection
Continuing convection in the mantle causes plates to move relative to each other.

The study of plate motion is called plate tectonics.

The motion of continents was first suspected by Sir Francis Bacon (17th cent). Best known for leading the scientific revolution with his new 'observation and experimentation' theory.
America and Europe are moving apart by 3 centimeters per year (≈ 30 km per million years). This “continental drift” is measured using GPS (global positioning systems).
The Moon

Moon diameter

\[ \text{=0.27 x Earth diameter} \]

Earth-Moon distance

\[ \text{=380,000 km} \]

\[ \text{=30 x Earth diameter} \]
The Moon

Apollo missions to the Moon (1969-1972)
Brought back 382 kg of rocks for chemical analysis, radioactive dating.
Where did the Moon come from?

Current favorite theory: COLLISIONAL EJECTION THEORY

A protoplanet the size of Mars struck the young Earth an oblique blow, just over 4.5 billion years ago.
Where did the Moon come from?

This dramatic collision likely happened when Earth was almost completely formed. Age of the Moon almost as old as the age of the oldest meteorites:

• Age of oldest Earth rocks = 4 billion years
• Age of oldest Moon rocks = 4.5 billion years
• Age of oldest meteorites (meteoroids that survive the plunge to Earth) = 4.56 billion years
Mercury’s unusual orbit

- Orbital period = 87.969 days
  Rotation period = 58.646 days = \((2/3) \times 87.969\) days

Mercury is **NOT** in synchronous rotation (1 rotation per orbit).
Instead, it has **3-to-2 spin-orbit coupling** (3 rotations for 2 orbits).
Synchronous rotation (WRONG!)

3-to-2 spin-orbit coupling (RIGHT!)
Time between one noon and the next is 176 days.
Sun is above the horizon for 88 days at the time.

Daytime temperatures reach as high as: 700 Kelvin (800 degrees F).
Nighttime temperatures drops as low as: 100 Kelvin (-270 degrees F).
Mercury has no moon

But is about the size of other planets’ moons!

- Ganymede: 5262 km
- Titan: 5150 km
- Mercury: 4880 km
- Callisto: 4806 km
- Io: 3642 km
- Moon: 3476 km
- Europa: 3138 km
- Triton: 2706 km
- Pluto: 2300 km
- Titania: 1580 km

The Largest Moons and Smallest Planets

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Mercury has no permanent atmosphere

It is **too hot** to retain an atmosphere (and has low escape speed).

Remember: **temperature** is a measure of the random speed of atoms (or molecules).

At a given temperature, massive atoms move more slowly than low-mass atoms.

\[ v = \sqrt{\frac{3kT}{m}} \]

- \( v \) = typical speed of atom
- \( T \) = temperature (Kelvin)
- \( m \) = mass of atom (molecule)
- \( k \) = a constant of nature
If an atom’s speed is greater than the escape speed, it will fly away on a hyperbolic orbit.

Low-mass atoms escape first, then “sluggish”, massive ones.

\[ v_{esc} = \sqrt{\frac{2GM}{r}} \]

- \( v \) = escape speed
- \( M \) = mass of planet
- \( r \) = radius of planet
- \( G \) = universal constant of gravitation
Daytime on **Earth**:  
\[ T = 300 \text{ Kelvin}, \ v_{\text{esc}} = 11.2 \text{ km/sec} \]  
Hydrogen and helium escape.

Daytime on **Mercury**:  
\[ T = 700 \text{ Kelvin}, \ v_{\text{esc}} = 4.3 \text{ km/sec} \]  
**All** gases escape.

Daytime on the **Moon**:  
\[ T = 260 \text{ Kelvin} \]  
\[ v_{\text{esc}} = 2.4 \text{ km/sec} \]  
Because \( v_{\text{esc}} \) is low, all gases escape, despite low \( T \).
Mariner 10

Only one spacecraft has visited Mercury: Mariner 10 (a fly-by) launched in November 1973.

It has only imaged 45% of Mercury’s surface.
Mercury’s surface

Like the Moon, Mercury has cratered highlands and smooth, lava-covered plains.

The hemisphere of Mercury that has been photographed resembles the Moon: (Crater walls are slightly lower.)
Highlands are heavily cratered.

Low-lying impact basins, such as the **Caloris basin**, are covered with smoother lava flows.
Mercury is exceptionally dense: 5400 km/m$^3$.

This is due to its extremely large iron-rich core.

The Earth is slightly denser, but only because it is compressed by its own strong gravity.

Mercury must have a huge dense core (probably mostly iron, like Earth’s).
Size of Mercury

Radius of Mercury = 2400 km.

Radius of iron core = 1800 km.
Return to Mercury

The MESSENGER spacecraft (MErcury Surface, Space ENviroment, GEnochemistry and Ranging)

Launched 2004: Mercury orbit in 2011
Venus

Venus is sometimes called Earth’s twin:
Radius = 95% of Earth’s
Mass = 82% of Earth’s
Surface gravity = 90% of Earth’s

Currently no Venusian moons, but an impact-created moon may have been absorbed in the past!
Venus’s orbit

Orbital period = 225 days
Rotation period = 243 days

Rotation of Venus is retrograde (probably caused by impact with a planetesimal).
On Venus, the time from noon to noon = 117 days
The surface of Venus is hidden from us by clouds of sulfuric acid. Venus has **100% cloud cover.** Its rotation speed can be found from radar signals which pierce the clouds (the same method used for Mercury, using Doppler effect).
Venus’s atmosphere

Venus is hot because of a runaway greenhouse effect.

Air pressure at the surface of Venus = 90 times air pressure on Earth (2/3 of a ton per square inch).
- 96.5% carbon dioxide (CO$_2$)
- 3.5% nitrogen (N$_2$)
- 0.015% sulfur dioxide (SO$_2$)
- Almost no water vapor

Surface temperature = 733 Kelvin (860 F)
Even hotter than Mercury!
The surface of Venus shows volcanic activity but no plate tectonics.

Because clouds are opaque, surface of Venus has been mapped using radar, by the spacecraft **Magellan**.

Round-trip travel time gives us the distance:

\[ d = \frac{t_2 - t_1}{2c} \]
Most of Venus is covered with rolling plains, but there are two large highland regions:

- Ishtar Terra (north) ~ Australia
- Aphrodite Terra (equator) ~ Africa
Many volcanoes, few impact craters

More than 1600 major volcanoes.

Estimated average age of crust = 500 million years (older than Earth, much younger than Mercury or Moon).

Perspective view of Venusian volcanoes

(Warning: vertical scale is exaggerated by a factor of 10):
Levels of volcanic activity

**Earth**: extremely active

**Venus**: mildly active

**Moon**: volcanically dead

**Mercury**: most likely volcanically dead
Similar to Earth’s interior.

Uncompressed density of Venus = uncompressed density of Earth = 4200 kg/m³.

Venus probably has a metal core and rocky mantle, like the Earth.
On the **Earth**, the cold rigid crust is broken into plates:

On **Venus**, the hot plastic crust does not break:

No plate tectonics on Venus.
Venus close up: Image returned by Venera 13 spacecraft (1982).
Mars

Mars is a fairly small planet:
Radius of Earth = 2 x radius of Mars
Radius of Mars = 2 x radius of Moon.
Mars

Mars is easy to observe from Earth.
Mars can be seen at **opposition**, when it is high in the sky at midnight.
Only a few wispy clouds, so the surface of Mars is easily seen (next page):
Visiting Mars

Mars is currently host to four orbiting spacecraft: Mars Global Surveyor, Mars Odyssey, Mars Express, and Mars Reconnaissance Orbiter. This is more than any planet other than Earth has. It is also home to the two Mars Exploration Rovers (*Spirit* and *Opportunity*).
Mars: revolution and rotation

Orbital period = 1.9 years
Rotation period = 24 hours, 37 minutes

Rotation axis of Mars is tilted by 25 degrees.
Martian seasons similar to Earth seasons (only longer).
Mars’s atmosphere

Mars has a tenuous atmosphere, with little water vapor and few clouds.
Average air pressure on Mars = 0.6% of sea level pressure on Earth.
Escape speed from Mars is comparable to that of Mercury; Mars is much cooler, so it has retained the more massive molecules like CO$_2$.
- 95% carbon dioxide (CO$_2$)
- 3% nitrogen (N$_2$)
- 0.03% sulfur dioxide (H$_2$O)
Little or no liquid water

Boiling point of water decreases as pressure drops.

**Sea level:** 100° Celsius

**Mt. Everest:** 75° Celsius

**Mars:** 5° Celsius = 278 Kelvin

On Mars, liquid water can exist only in a very limited temperature range.
Little water vapor

There is little water vapor in the Martian atmosphere because ultraviolet light breaks it up:

$$\text{H}_2\text{O} + \text{UV photon} \rightarrow \text{H}_2 + \text{O}$$

Hydrogen escapes into space.

Oxygen bonds with iron in the soil, making rust.
Mars’s atmosphere

Low density atmosphere implies:
(1) small **greenhouse effect**
(2) large temperature swings.

**Summer on Mars:**
High = 260 Kelvin
Low = 200 Kelvin

**Summer in Earth’s deserts:**
High = 310 Kelvin
Low = 290 Kelvin
Martian clouds are made of ice crystals: frozen $\text{H}_2\text{O}$, frozen $\text{CO}_2$. 
Martian icecaps

Icecaps at the north and south poles of Mars are also made of ice: frozen H$_2$O, frozen CO$_2$.

Icecaps shrink in **summer**, grow in **winter**.
Mars has large volcanoes and a huge rift valley, but no plate tectonics

Two hemispheres of Mars are very different from each other.

**North:**
recent volcanic activity (like Earth and Venus).

**South:**
heavily cratered highlands (like Moon and Mercury).
Topographical map of Mars
Mars interior:
Robotic “rovers” have given us a close-up look at Mars

Spirit and Opportunity (operated since January 2004) are taking images and spectra of Mars rocks.

Success!!
What have Spirit and Opportunity done for us?

- Sent back spectacular pictures:

- Found sedimentary rocks that show chemical evidence of having been soaked in water.
Mars’s moons

**Phobos** (“fear”):
- 28 kilometers long.

**Deimos** (“panic”):
- 16 kilometers long.
- Irregular in shape, undifferentiated.
- Probably captured asteroids.
Random fact of the day

Phobos orbits Mars in less than 8 hours.

Mars takes more than 24 hours for one rotation (Martians would see Phobos rise in west, set in east!)

Tidal bulge of Mars lags behind Phobos, tugging it onto a smaller orbit (Crush! In 40 million years).
Unusual moons for some of the planets may be captured planetesimals, e.g. Mars’ moons:

(a) Phobos

(b) Deimos