The solar system
The Sun

- Over 99.8% of solar system's mass
- Made mostly of H/He gas (plasma)
- Converts 4 million tons of mass into energy each second (E=mc²)
Mercury

- Made of metal and rock; large iron core
- Desolate, cratered; long, tall, steep cliffs
- Very hot and very cold: 425°C (day), –170°C (night)
Venus

• Nearly identical in size to Earth; surface hidden by clouds
• Hellish conditions due to an extreme greenhouse effect
• Even hotter than Mercury: 470°C, day and night
• Rotates in the “wrong” direction
Earth

- An oasis of life
- The only surface liquid water in the solar system
- A surprisingly large moon
Mars

- Giant volcanoes, a huge canyon, polar caps, and more
- Water flowed in the distant past; could there have been life?
Mars
Mars
Mars
Jupiter

- Much farther from Sun than inner planets
- Mostly H/He; no solid surface
- 300 times more massive than Earth
- Many moons, rings
Jupiter

Has interesting moons:

- Io (shown here): Active volcanoes all over
- Europa: Possible subsurface ocean
- Ganymede: Largest moon in solar system
- Callisto: A large, cratered "ice ball"
Saturn

- Giant and gaseous like Jupiter
- Spectacular rings
- Many moons
Saturn

The rings are NOT solid; they are made of countless small chunks of ice and rock, each orbiting like a tiny moon.
Uranus

- Smaller than Jupiter/Saturn; much larger than Earth
- Made of H/He gas and hydrogen compounds (H$_2$O, NH$_3$, CH$_4$)
- Extreme axis tilt
- Moons and rings
Neptune

- Similar to Uranus (except for axis tilt)
- Many moons (including Triton, which orbits backwards)
Pluto and other dwarf planets

- Much smaller than other planets
- Icy, comet-like composition
- Pluto's moon Charon is similar in size to Pluto
Pluto
Asteroids
Asteroids
Comets
Comets
Comets
Some basic facts about the solar system: similar spin and orbital rotation among the planets

All of the major planets:

- lie approximately in the same plane
- follow ~circular orbits
- *orbit* in the same direction, and in the same direction as the Sun’s rotation
- *rotate* in the same direction and have axes of rotation that are ~perpendicular to the orbital plane (with the exceptions of Venus and Uranus)
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- have moons that also orbit in the same direction (with the exceptions of Mercury and Venus which don’t have moons, and Neptune that has a moon orbiting in the opposite direction)
Some basic facts about the solar system: two kinds of (major) planets

- The four inner planets (Mercury, Venus, Earth, and Mars) are relatively small, and are rocky. These are the **terrestrial planets**

- The four outer planets — Jupiter, Saturn, Uranus, and Neptune — are larger, more massive, and made primarily of hydrogen and helium gas. These are the **jovian planets** (aka **gas giants**).
Some basic facts about the solar system:

- **Asteroids** are small rocky objects, and most are orbiting in the **asteroid belt** between Jupiter and Mars.
Some basic facts about the solar system: comets

- Comets are small objects of rock and ice (dirty snowballs)
- 1000s exist out in the **Kuiper belt** beyond Neptune, and many more than that exist out in the spherical **Oort cloud** surrounding our solar system.
- Some have highly elliptical orbits, and come into the inner regions of the solar system and heat up. Then we can see their tails of melted material.
How did the solar system form?

Characteristics of the solar system that we need to explain:

- What causes the orderly patterns of rotation?
- Why are there two major types of planets?
- Where did the asteroids and comets come from?
- How do we explain the exceptions to the rules?
Stars form out of clouds of gas

nebula = cloud
Stars form out of clouds of gas

most of the gas consists of the lightest elements, hydrogen and helium, with small amounts of heavier elements
06_CollapseSolarNebula
06_FormProtoplanetaryDisk
The formation of a hot protostellar core and protoplanetary disk
The formation of a hot protostellar core and protoplanetary disk
Q: Why does the gaseous material heat up as it collapses?

A. Conservation of angular momentum
B. Conservation of energy
C. Nuclear reactions in the protostellar core
D. Friction in the rotating material
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A. Conservation of angular momentum

B. Conservation of energy

C. Nuclear reactions in the protostellar core

D. Friction in the rotating material
The nebular theory of solar system formation

• A nebula becomes dense and massive enough to start self-gravitating. It begins collapsing.

• But because it has some net angular momentum, it begins rotating very rapidly. So there is a limit to how much it can collapse in the plane of rotation, but it can fully collapse in the vertical direction, leaving a spinning protoplanetary disk with a dense protostellar core

• The gas heats up as it contracts; gravitational potential energy -> thermal energy
The “nebular theory” of solar system formation

Planets condense out of the protoplanetary disk

Inside of the **frost line**, only rocks and metals can condense into **planetesimals**, and hydrogen compounds (including water) remain in a gaseous state. But beyond the frost line hydrogen compounds can also condense into ices.
<table>
<thead>
<tr>
<th>Component</th>
<th>Examples</th>
<th>Typical condensation temperature</th>
<th>Relative abundance (by mass)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen and Helium Gas</td>
<td>hydrogen, helium</td>
<td>do not condense in nebula</td>
<td>98%</td>
</tr>
<tr>
<td>Hydrogen Compounds</td>
<td>water (H₂O), methane (CH₄),</td>
<td>&lt;150 K</td>
<td>1.4%</td>
</tr>
<tr>
<td></td>
<td>ammonia (NH₃)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rock</td>
<td>various minerals</td>
<td>500–1300 K</td>
<td>0.4%</td>
</tr>
<tr>
<td>Metals</td>
<td>iron, nickel, aluminum</td>
<td>1000–1600 K</td>
<td>0.2%</td>
</tr>
</tbody>
</table>
The nebular theory of solar system formation

• But there simply isn’t much rocky material and metals around, so the planetesimals inside the frost line never become very big -> so the inner terrestrial planets are relatively small and rocky

• However the outer planetesimals have a lot more hydrogen, helium, and hydrogen compounds that can condense. So they can become much more massive, and due to their gravitational force can start attracting even more material -> so the outer jovian planets are large and contain mostly hydrogen, helium, and hydrogen compounds
Eventually the protostellar core becomes so hot, and so dense, that it begins to undergo nuclear reactions. It becomes a star.
The nebular theory of solar system formation

The protoplanetary disk begins to clear out because:

- The planets accrete the material around them
- The planets eject material that they don’t accrete by gravitational perturbations
- After the star begins to shine brightly it eject winds, blowing out remaining diffuse material
How does this theory explain the asteroids and comets?

- The remaining planetesimals within the frost line are asteroids in the asteroid belt.
- The remaining planetesimals outside of the frost line are comets in the Kuiper belt.
How does this theory explain the asteroids and comets?

A huge number of planetesimals have been ejected due to gravitational encounters with other planets. Only (some of) those within the asteroid belt and within the Kuiper belt are on stable orbits. The rest have been flung far out into the Oort cloud, some of which remain on highly elliptical orbits and plunge back into the solar system.
What about the dwarf planets?
What about the dwarf planets?

Pluto exists out in the Kuiper belt, along with a number of other similarly-large objects.
What about the dwarf planets?
What about the dwarf planets?

These objects are clearly different from the large, gas-rich jovian planets, and there’s a lot of them. Their actually more like large comets. So now we’ve reclassified the largest amongst them — the ones that are massive enough to become spherical due to their own gravity — as “dwarf planets.”
How do planets get their moons? Three ways…

The moons of the jovian planets probably formed out of disks in the same way that the planets formed out of the protoplanetary disk.
How do planets get their moons? Three ways…

There may not have been enough rocks/metals around for the terrestrial planets to form significant disks, and therefore moons. Mercury and Venus don’t have moons. However Mars has two moons which may have been asteroids that were gravitationally captured.
How do planets get their moons? Three ways…

There may not have been enough rocks/metals around for the terrestrial planets to form significant disks, and therefore moons. Mercury and Venus don’t have moons. However Mars has two moons which may have been asteroids that were gravitationally captured.

Neptune also has a moon that orbits in the “wrong” direction, so that may also have been gravitationally captured.
How do planets get their moons? Three ways...

So then how do we explain our Moon? It is too large for gravitational capture. It also has a significantly lower density than the Earth, suggesting that it did not form in a disk of the same material...
How do planets get their moons? Three ways…

The **giant impact hypothesis** — when the Earth was young it may have collided with another smaller (Mars-sized) planet, spewing debris out into a ring which eventually condensed into the Moon.
How do planets get their moons? Three ways...

The giant impact hypothesis would explain why:

- The Moon is so large relative to the Earth
- The Moon has a similar chemical composition as the outer layers of the Earth, even though it is less dense overall
- The tilt of the Earth’s axis (23° from perpendicular to the ecliptic)
How do planets get their moons? Three ways…

- Formation in a disk (probably only happened for the jovian planets)
- gravitational capture (can happen anywhere)
- giant impact (can happen anywhere)
Age of the solar system

The most accurate way to determine the age of the solar system is through radiometric dating (also called radioactive dating)

- The atoms of certain elements can spontaneously decay into other kinds of elements
- Example: potassium-40 (19 protons and 21 neutrons) decays into argon-40 (18 protons and 22 neutrons) with a half-life of 1.25 billion years. This means that after 1.25 billion years, half of the potassium has become argon. After another 1.25 billion years, half the remaining potassium also becomes argon. And so on.
Age of the solar system

The amount of potassium-40 decreases over time, because it decays into argon-40.

The amount of argon-40 increases as potassium-40 decays.

Result: The precise proportions of the two isotopes tell us the age of the rock.
Age of the solar system

- If we can be confident that rocks initially contained no argon-40 (and we can!), then by measuring the relative amounts of potassium-40 and argon-40 we can figure out how much time has gone by.

- The oldest rocks that we’ve found (from the Earth, Moon, and from meteorites) are all about 4.5 billion years old. This agrees with independent estimates of how old the Sun is, therefore we’re pretty confident about the age of the solar system.