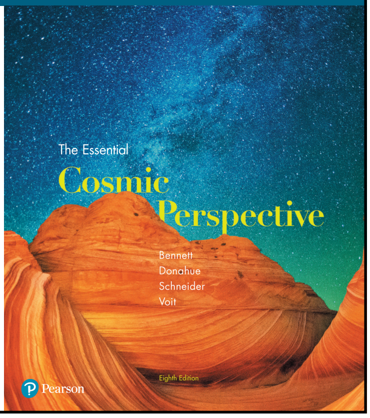
Lecture Outline

Chapter 6: Formation of the Solar System



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1

6.1 A Brief Tour of the Solar System

Our goals for learning:

- What does the solar system look like?

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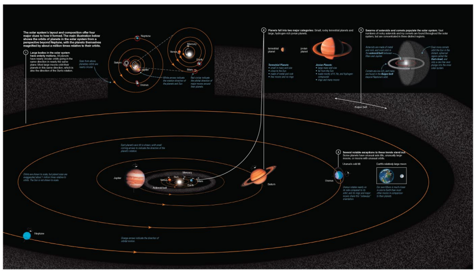
What does the solar system look like?



The solar system exhibits clear patterns of composition and motion.

These patterns are far more important and interesting than numbers, names, and other trivia.

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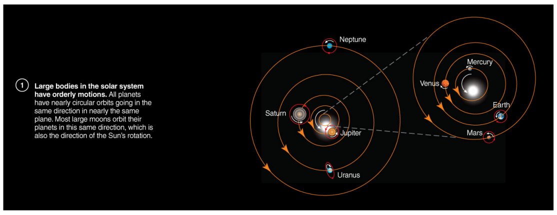
What does the solar system look like?



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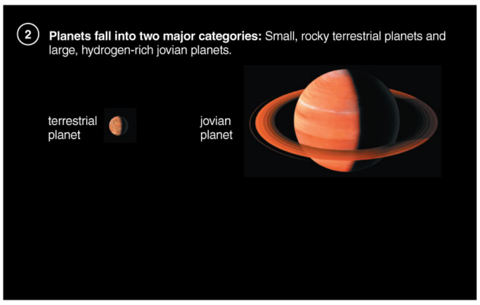
What does the solar system look like?



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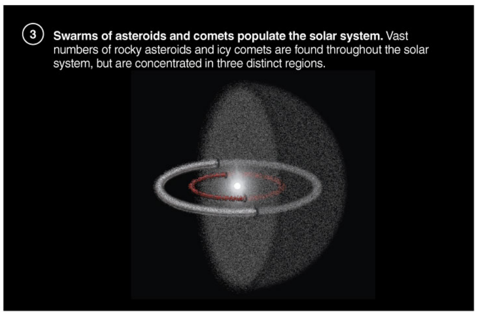
What does the solar system look like?



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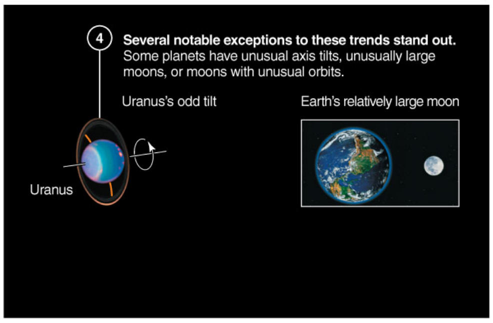
What does the solar system look like?



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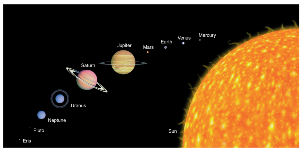
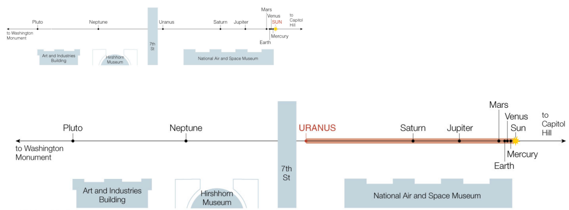


Planets are very tiny compared to distances between them.



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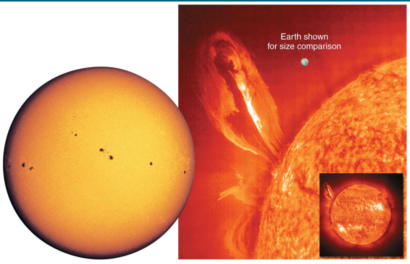
Sun



a A visible-light photograph of the Sun's surface. The dark splotches are sunspots—each large enough to swallow several Earths.

b This ultraviolet photograph, from the *SOHO* spacecraft, shows a huge streamer of hot gas on the Sun. The image of Earth was added for size comparison.

- 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

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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)

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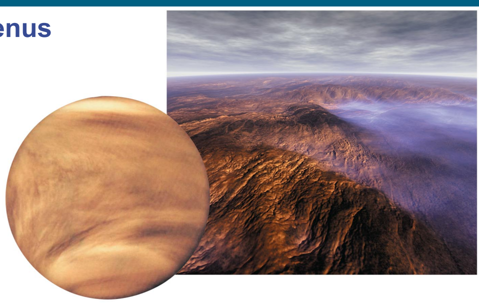
Venus



- 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

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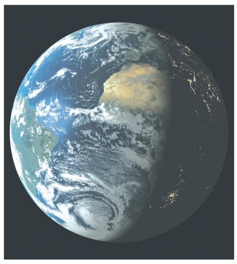
Earth

Earth and Moon to scale



a This image (left), computer generated from satellite data, shows the striking contrast between the day and night hemispheres of Earth. The day side reveals little evidence of human presence, but at night our presence is revealed by the lights of human activity. (From the Voyage scale model solar system, developed by the Challenger Center for Space Science Education, the Smithsonian Institution, and NASA. Image created by ARC Science Simulations © 2001.)

b Earth and the Moon, shown to scale. The Moon is about 1/4 as large as Earth in diameter, while its mass is about 1/80 of Earth's mass. To show the distance between Earth and Moon on the same scale, you'd need to hold these two photographs about 1 meter (3 feet) apart.

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

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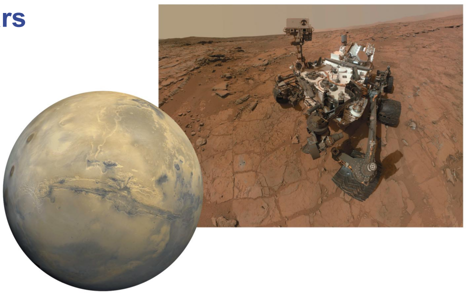
Mars



- Looks almost Earth-like, but don't go without a spacesuit!
- Giant volcanoes, a huge canyon, polar caps, and more
- Water flowed in the distant past; could there have been life?

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Jupiter

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

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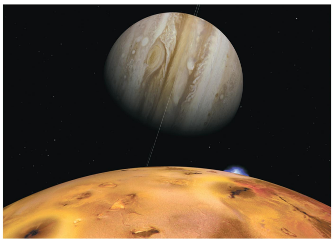

Jupiter's moons can be as interesting as planets themselves, especially Jupiter's four *Galilean moons.*

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

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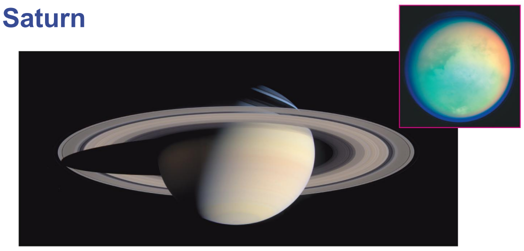
Saturn



- Giant and gaseous like Jupiter
- Spectacular rings
- Many moons, including cloudy Titan

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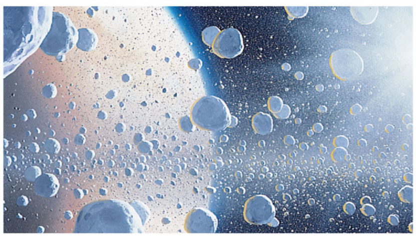

Rings are NOT solid; they are made of countless small chunks of ice and rock, each orbiting like a tiny moon.

Artist's conception of Saturn's rings

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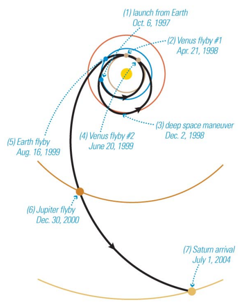
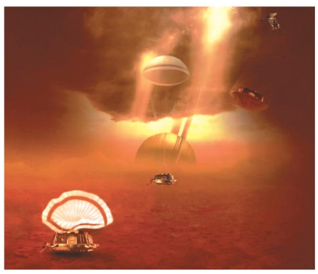


a The trajectory of *Cassini* to Saturn



- *Cassini* probe arrived in July 2004 (launched in 1997).

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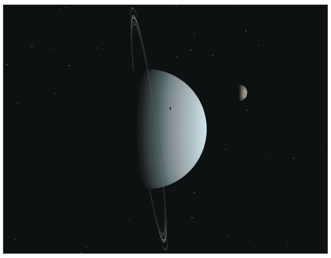
Uranus



- Smaller than Jupiter/Saturn; much larger than Earth
- Made of H/He gas and **hydrogen compounds** (H_2O, NH_3, CH_4)
- Extreme axis tilt
- Moons and rings

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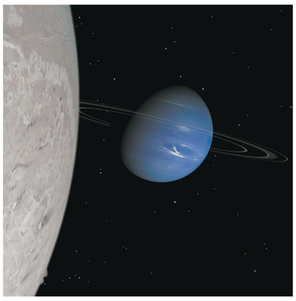
Neptune



- Similar to Uranus (except for axis tilt)
- Many moons (including Triton)

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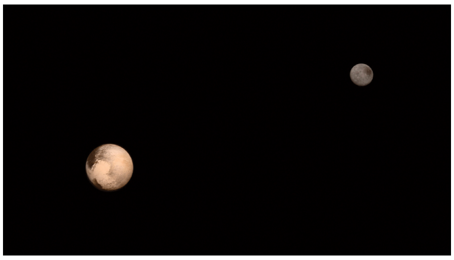
Pluto and Other Dwarf Planets



- Much smaller than other planets
- Icy, comet-like composition
- Pluto's moon Charon is similar in size to Pluto

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6.2 The Nebular Theory of Solar System Formation

Our goals for learning:

- What features of our solar system provide clues to how it formed?
- What is the nebular theory?

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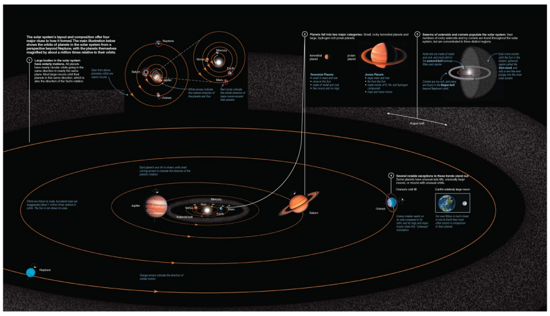
What features of our solar system provide clues to how it formed?



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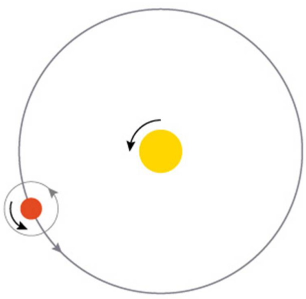
Motion of Large Bodies



- All large bodies in the solar system orbit in the same direction and in nearly the same plane.
- Most also rotate in that direction.

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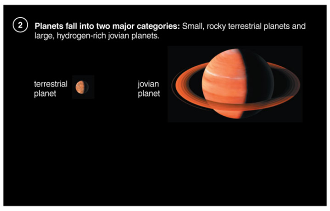
Two Major Planet Types



- Terrestrial planets are rocky, relatively small, and close to the Sun.
- Jovian planets are gaseous, larger, and farther from the Sun.

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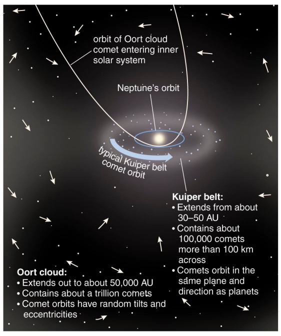
Swarms of Smaller Bodies



- Many rocky asteroids and icy comets populate the solar system.

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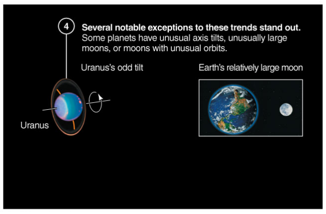
Notable Exceptions



- Several exceptions to normal patterns need to be explained.

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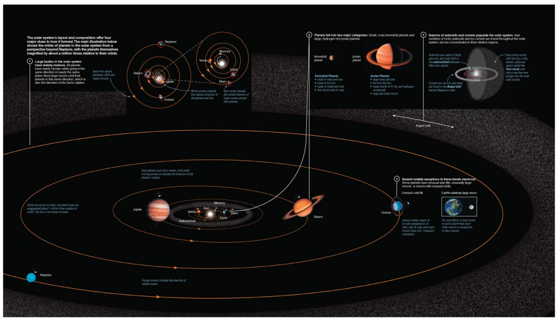
What is the nebular theory?



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According to the **nebular theory,** our solar system formed from a giant cloud of interstellar gas.

(**nebula** = cloud)

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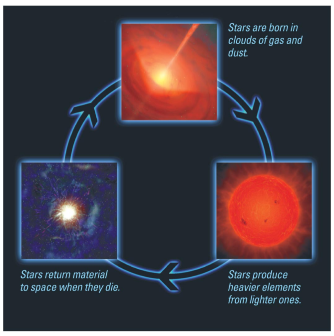
Origin of the Nebula



- Elements that formed planets were made in stars and then recycled through interstellar space.

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Evidence from Other Gas Clouds

- We can see stars forming in other interstellar gas clouds, lending support to the nebular theory. Here we see the Orion nebula, with six insets showing nascent solar systems forming.

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6.3 Explaining the Major Features of the Solar System

Our goals for learning:

- What caused the orderly patterns of motion?
- Why are there two major types of planets?
- Where did asteroids and comets come from?
- How do we explain the "exceptions to the rules"?

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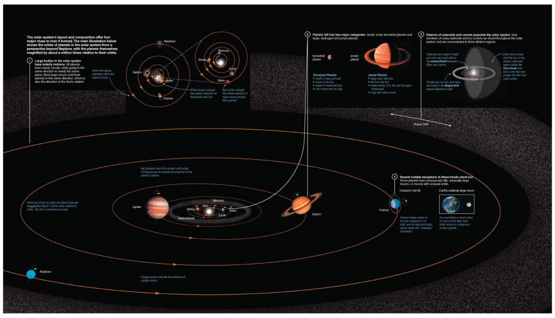
What caused the orderly patterns of motion?



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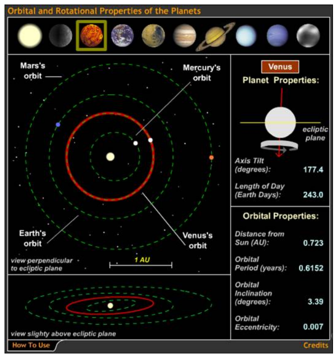

PLAY Orbital and Rotational Properties of the Planets

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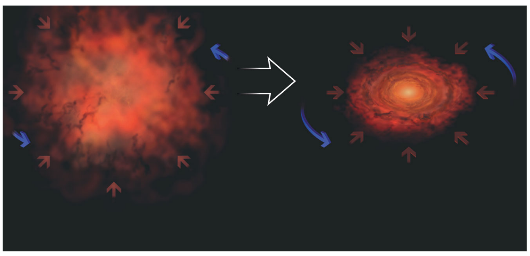
Conservation of Angular Momentum



- The rotation speed of the cloud from which our solar system formed must have increased as the cloud contracted.

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Rotation of a contracting cloud speeds up for the same reason a skater speeds up as she pulls in her arms.

PLAY Collapse of the Solar Nebula

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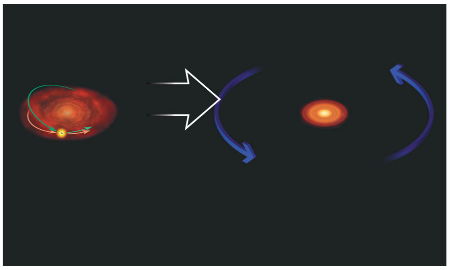
Flattening



- Collisions between particles in the cloud caused it to flatten into a disk.

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Collisions between gas particles in a cloud gradually reduce random motions.

PLAY Formation of Circular Orbits

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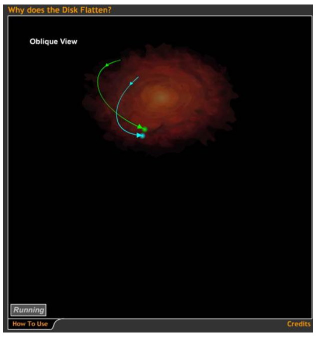

Collisions between gas particles also reduce up and down motions.

PLAY Why Does the Disk Flatten?

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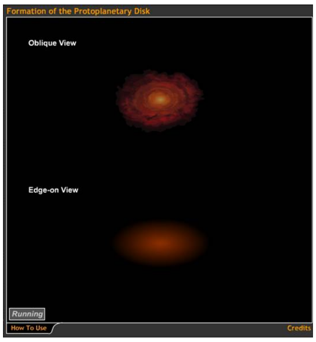

The spinning cloud flattens as it shrinks.

PLAY Formation of the Protoplanetary Disk

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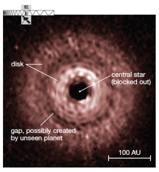
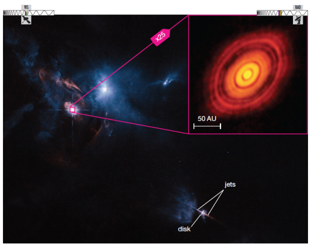
Disks Around Other Stars



a This Hubble Space Telescope image shows a flattened, spinning disk around the star TW Hydrae. This particular disk also shows at least one circular "gap" in which material seems to have been cleared away, probably by a planet forming in the disk, which would have a gravitational attraction that would tend to sweep up material along its path.



b The inset, from the Atacama Large Millimeter/submillimeter Array (ALMA), shows a disk around a star named HL Tauri; the concentric gaps in the disk are almost certainly regions being cleared as planets form. The disk diameter is about three times that of Neptune's orbit around the Sun. The background image, from the Hubble Space Telescope, shows the star-forming region in which this disk is located. Another disk, seen edge-on with jets extending outward, appears at lower right.

- Observations of disks around other stars support the nebular hypothesis.

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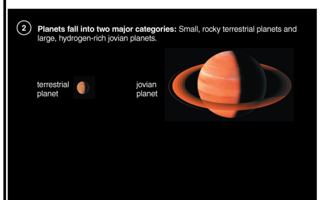
Why are there two major types of planets?



A summary of the four types of materials present in the solar nebula. The squares represent the relative proportions of each type (by mass).

	Examples	Can condense at temperatures below	Relative abundance (by mass)
Hydrogen and Helium Gas	hydrogen, helium	do not condense in nebula	98%
Hydrogen Compounds	water (H_2O), methane (CH_4), ammonia (NH_3)	150 K	1.4%
Rock	various minerals	500–1300 K	0.4%
Metals	iron, nickel, aluminum	1000–1600 K	0.2%

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Conservation of Energy

As gravity causes the cloud to contract, it heats up.

PLAY Collapse of the Solar Nebula

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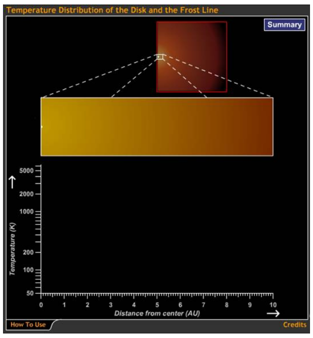

- Inner parts of the disk are hotter than outer parts.
- Rock can be solid at much higher temperatures than ice.

PLAY Temperature Distribution of the Disk and the Frost Line

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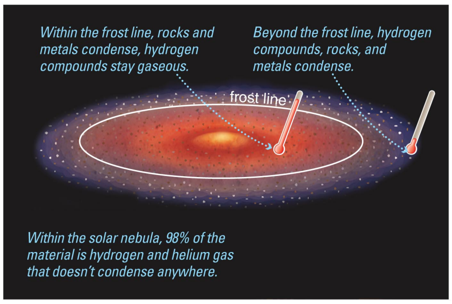

- Inside the ***frost line***: Too hot for hydrogen compounds to form ices
- Outside the ***frost line***: Cold enough for ices to form

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Formation of Terrestrial Planets

- Small particles of rock and metal were present inside the frost line.
- Planetesimals of rock and metal built up as these particles collided.
- Gravity eventually assembled these planetesimals into terrestrial planets.

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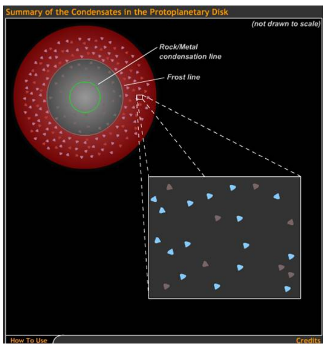

Tiny solid particles stick to form ***planetesimals***.

PLAY Summary of the Condensates in the Protoplanetary Disk

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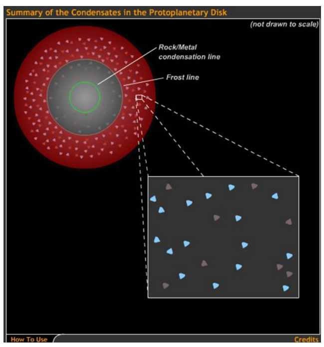

Gravity draws ***planetesimals*** together to form planets.

This process of assembly is called ***accretion.***

PLAY Summary of the Condensates in the Protoplanetary Disk

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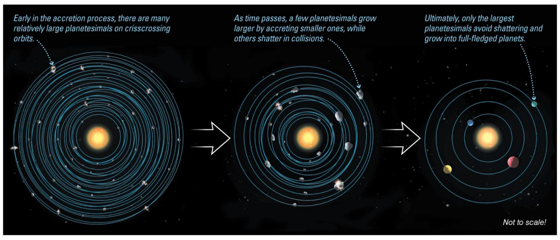
Accretion of Planetesimals



- Many smaller objects collected into just a few large ones.

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Formation of Jovian Planets

- Ice could also form small particles outside the frost line.
- Larger planetesimals and planets were able to form.
- The gravity of these larger planets was able to draw in surrounding H and He gases.

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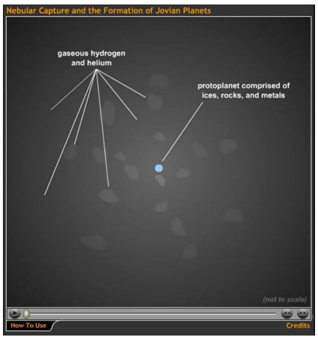

The gravity of rock and ice in jovian planets draws in H and He gases.

PLAY Nebular Capture and the Formation of the Jovian Planets

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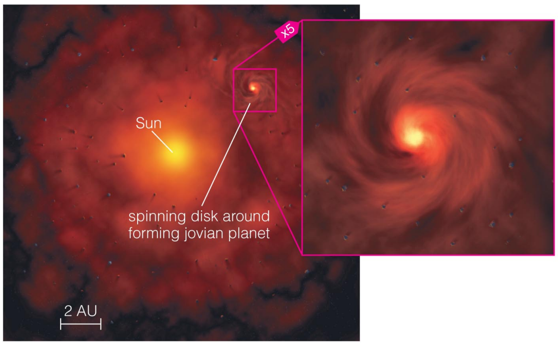

- Moons of jovian planets form in miniature disks.

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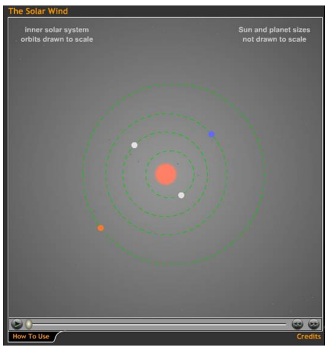

Radiation and outflowing matter from the Sun—the ***solar wind***—blew away the leftover gases.

PLAY The Solar Wind

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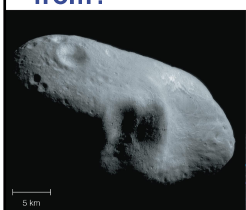
Where did asteroids and comets come from?



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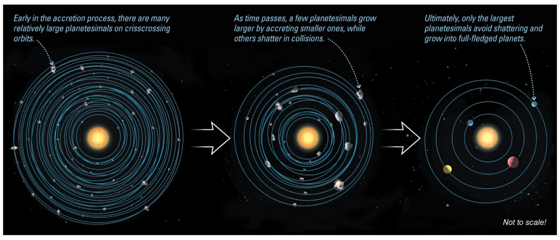
Asteroids and Comets



- Leftovers from the accretion process
- Rocky asteroids inside frost line
- Icy comets outside frost line

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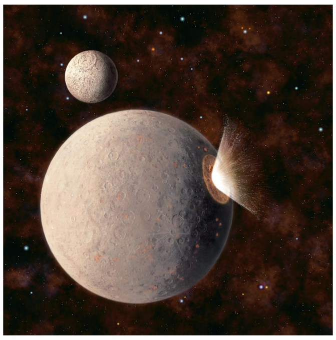
Heavy Bombardment



- Leftover planetesimals bombarded other objects in the late stages of solar system formation.

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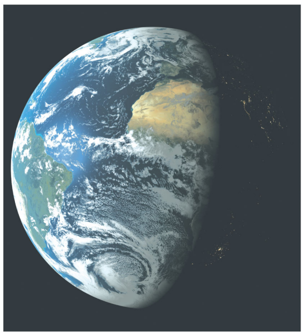
Origin of Earth's Water



- Water may have come to Earth by way of icy planetesimals from the outer solar system.

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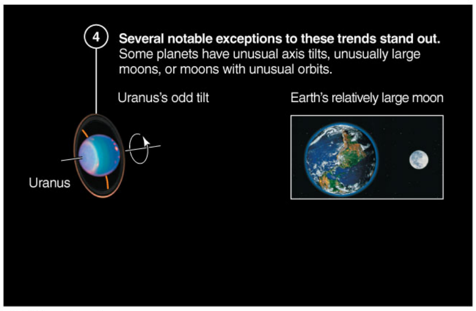
How do we explain "exceptions to the rules"?



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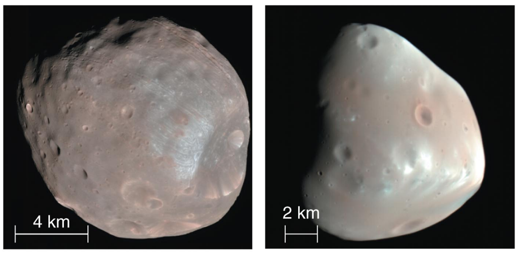
Captured Moons



a Phobos   b Deimos

- The unusual moons of some planets may be captured planetesimals.

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Giant Impact

…then accreted into the Moon.

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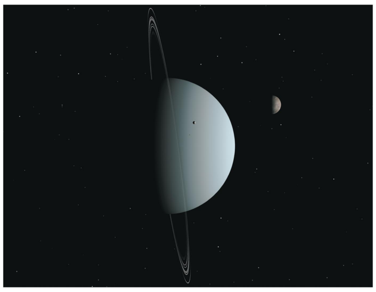
Odd Rotation



- Giant impacts might also explain the different rotation axes of some planets.

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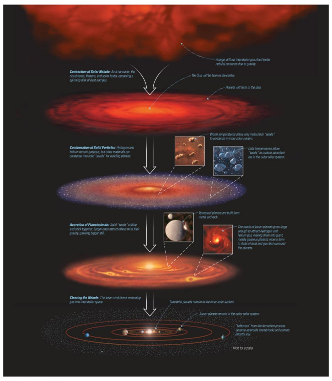

- Review of the nebular theory

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Thought Question

How would the solar system be different if the solar nebula had cooled with a temperature half its current value?

A. Jovian planets would have formed closer to the Sun.
B. There would be no asteroids.
C. There would be no comets.
D. Terrestrial planets would be larger.

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Thought Question

How would the solar system be different if the solar nebula had cooled with a temperature half its current value?

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C. There would be no comets.
D. Terrestrial planets would be larger.

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Thought Question

Which of these facts is NOT explained by the nebular theory?

A. There are two main types of planets: terrestrial and jovian.
B. Planets orbit in the same direction and plane.
C. Asteroids and comets exist.
D. There are four terrestrial and four jovian planets.

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Thought Question

Which of these facts is NOT explained by the nebular theory?

A. There are two main types of planets: terrestrial and jovian.
B. Planets orbit in the same direction and plane.
C. Asteroids and comets exist.
D. There are four terrestrial and four jovian planets.

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6.4 The Age of the Solar System

Our goals for learning:

- How do we know the age of the solar system?

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How do we know the age of the solar system?

- We cannot find the age of a planet, but we can find the ages of the rocks that make it up.
- We can determine the age of a rock through careful analysis of the proportions of various atoms and isotopes within it.

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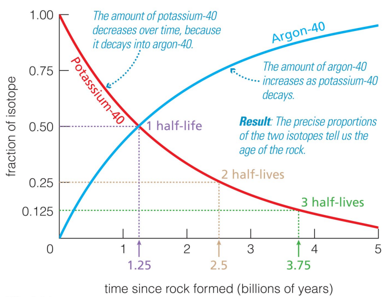
Radioactive Decay



- Some isotopes decay into other nuclei.
- A **half-life** is the time for half the nuclei in a substance to decay.

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Thought Question

Suppose you find a rock originally made of potassium-40, half of which decays into argon-40 every 1.25 billion years. You open the rock and find 15 atoms of argon-40 for every atom of potassium-40. How long ago did the rock form?

A. 1.25 billion years ago
B. 2.5 billion years ago
C. 3.75 billion years ago
D. 5 billion years ago

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Thought Question

Suppose you find a rock originally made of potassium-40, half of which decays into argon-40 every 1.25 billion years. You open the rock and find 15 atoms of argon-40 for every atom of potassium-40. How long ago did the rock form?

A. 1.25 billion years ago
B. 2.5 billion years ago
C. 3.75 billion years ago
D. 5 billion years ago

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Dating the Solar System

Age dating of meteorites that are unchanged since they condensed and accreted tells us that the solar system is about 4.6 billion years old.

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Dating the Solar System

- Radiometric dating tells us that the oldest moon rocks are 4.4 billion years old.
- The oldest meteorites are 4.55 billion years old.
- Planets probably formed 4.5 billion years ago.

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