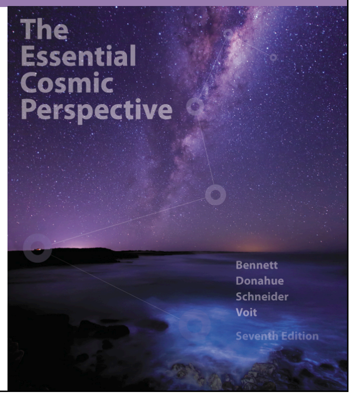
Lecture Outline

Chapter 6: Formation of the Solar System

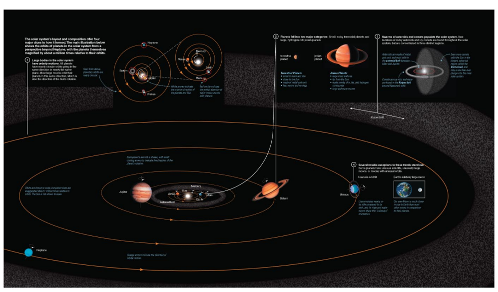


6.1 A Brief Tour of the Solar System

Our goals for learning:

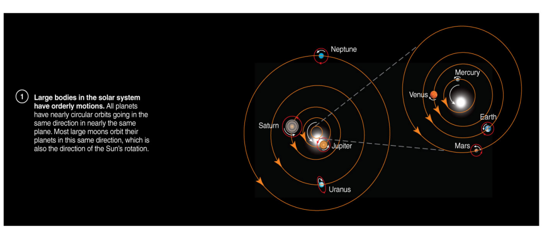
- ➢ What does the solar system look like?

➢What does the solar system look like?



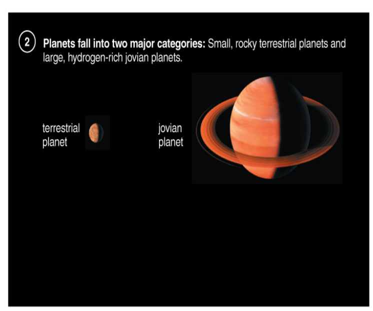
- ❑ The solar system exhibits clear patterns of composition and motion.
  - Planets orbit the Sun in the same direction and nearly in the same plane.
  - Inner planets characteristics differ from outer planets.
  - Smaller objects are concentrated in specific regions.

Large Bodies in the solar system have orderly motions.



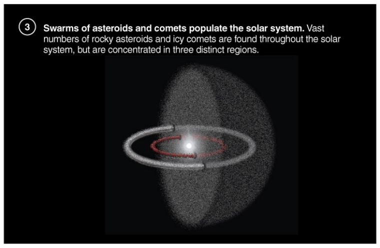
Planets and moons orbit and rotate in the same direction as the the Sun (with a few exceptions).

Planets fall into two major categories.



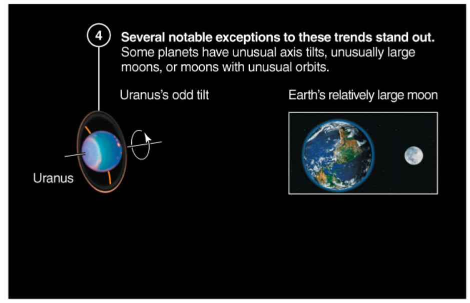
- ❑ Terrestrial
  - Rocky
  - Metal
- ❑ Jovian
  - Hydrogen

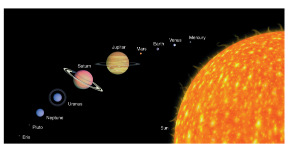
Asteroids and comets are concentrated in three distinct regions



- ❑ Asteroid belt
- ❑ Kuiper Belt
- ❑ Oort Cloud

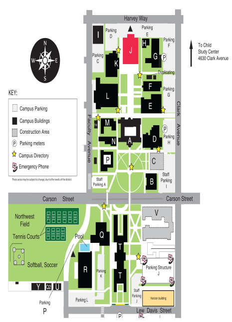
Noticeable exceptions



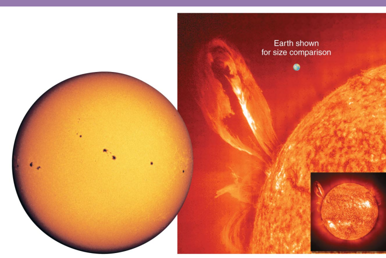


Planets are very tiny compared to distances between them.

Recall: Solar System walk



Sun



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

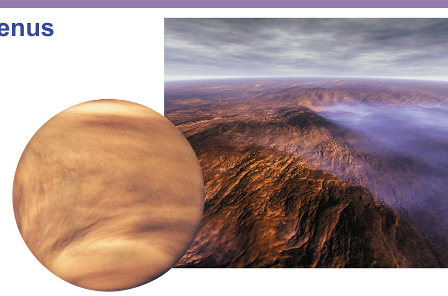
b This ultraviolet photograph, from the *SOHO* spacecraft, shows a huge streamer of hot gas on the Sun. The image of Earth was added for size comparison.

- ❑ Over 99.8% of solar system's mass
- ❑ 98% H/He gas (plasma), 2% other elements
- ❑ You can fit 108 Earths across

Mercury

- ❑ Made of metal and rock; large iron core
- ❑ Desolate, cratered; long, tall, steep cliffs
- ❑ Very hot and very cold: 800°F (day), -280°F (night)

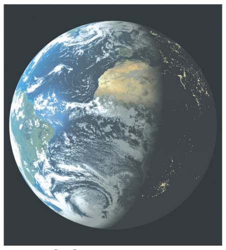
Venus



- ❑ Nearly identical in size to Earth; surface hidden by clouds
- ❑ Hellish conditions due to an extreme **greenhouse effect**
- ❑ Even hotter than Mercury: nearly 900°F, day and night

Earth

Earth and Moon to scale

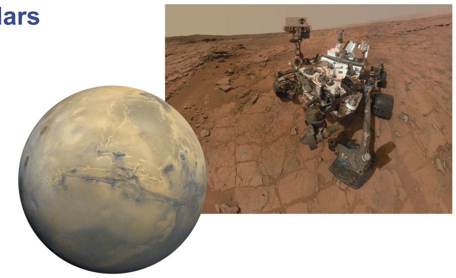


a This image (left), computer generated from satellite data, shows the striking contrast between the day and night hemispheres of Earth. The day side reveals little evidence of human presence, but at night our presence is revealed by the lights of human activity. (From the Voyage scale model solar system, 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

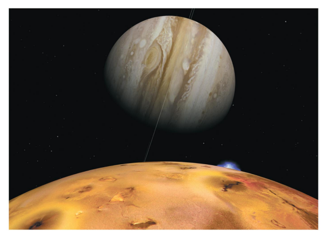
Mars



- 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?

Jupiter

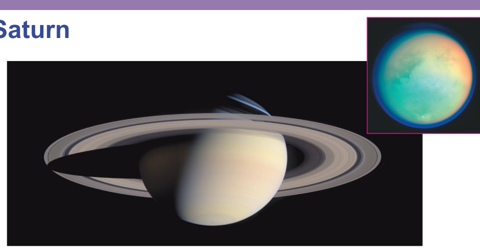
- Much farther from Sun than inner planets
- Mostly H/He; no solid surface
- Massive: you could fit over 1000 Earths inside
- Many moons 67+, rings



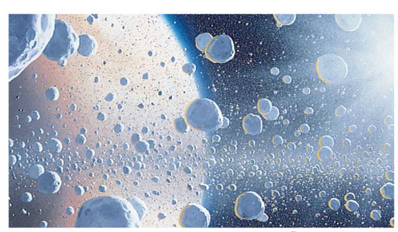
Jupiter's moons can be as interesting as planets themselves, especially Jupiter's four *Galilean moons.*

- Io: (young surface) Active volcanoes
- Europa: (smooth surface) Possible subsurface ocean
- Ganymede: Largest moon in solar system
- Callisto: (old surface) A large, cratered "ice ball"

Saturn



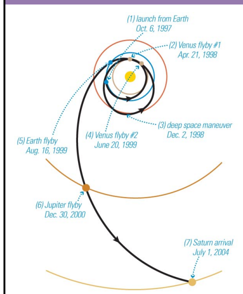
- Giant and gaseous like Jupiter
- Spectacular rings
- Many moons 62+, including cloudy Titan
- Density .70 g/cm^3 *(water has density of 1 g/cm^3)*



MA INTERACTIVE FIGURE

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

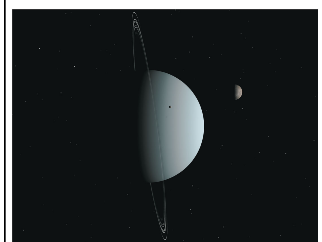
Artist's conception of Saturn's rings



a The trajectory of *Cassini* to Saturn

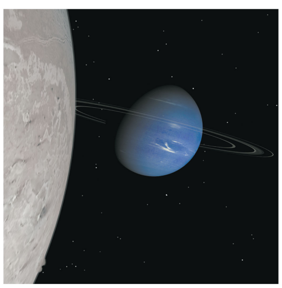
- *Cassini* probe arrived in July 2004 (launched in 1997).

Uranus



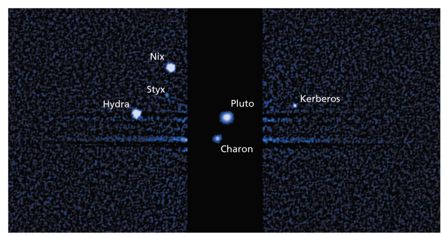
- Smaller than Jupiter/ Saturn; much larger than Earth
- Made of H/He gas and **hydrogen compounds** (H_2O, NH_3, CH_4)
- Extreme axis tilt
- Moons 27+ and rings

Neptune



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

Pluto and Other Dwarf Planets



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

Specifications to know

TABLE 7.1 The Planetary Data[a]

Photo	Planet	Relative Size	Average Distance from Sun (AU)	Average Equatorial Radius (km)	Mass (Earth = 1)	Average Density (g/cm^3)	Orbital Period	Rotation Period	Axis Tilt	Average Surface (or Cloud-Top) Temperature[b]	Composition	Known Moons (2015)	Rings?
	Mercury	·	0.387 .4	2440	0.055	5.43	87.9 days	58.6 days	0.0°	700 K (day) 100 K (night) -280F 800F	Rocks, metals	0	No
	Venus	•	0.723 .7	6051	0.82	5.24	225 days	243 days slow	177.3° ccw	740 K 900F	Rocks, metals	0	No
	Earth	•	1.00	6378	1.00	5.52	1.00 year	23.93 hours	23.5°	290 K	Rocks, metals	1	No
	Mars	·	1.52 1.5	3397	0.11	3.93	1.88 years	24.6 hours	25.2°	220 K	Rocks, metals	2	No
	Jupiter	●	5.20 5	71,492	318	1.33	11.9 years	9.93 hours	3.1°	125 K	H, He, hydrogen compounds[c]	67 60+	Yes
	Saturn	●	9.54 10	60,268	95.2	0.70	29.5 years	10.6 hours	26.7°	95 K	H, He, hydrogen compounds[c]	62 60+	Yes
	Uranus	●	19.2 20	25,559	14.5	1.32	83.8 years	17.2 hours	97.9° side	60 K	H, He, hydrogen compounds[c]	27 30-	Yes
	Neptune	●	30.1 30	24,764	17.1	1.64	165 years	16.1 hours	29.6°	60 K	H, He, hydrogen compounds[c]	14 15-	Yes
	Pluto	·	39.5 40	1185	0.0022	1.9	248 years	6.39 days	112.5°	44 K	Ices, rock	5	No
	Eris	·	67.7 70	1168	0.0028	2.3	557 years	1.08 days	78°	43 K	Ices, rock	1	No

Freezing

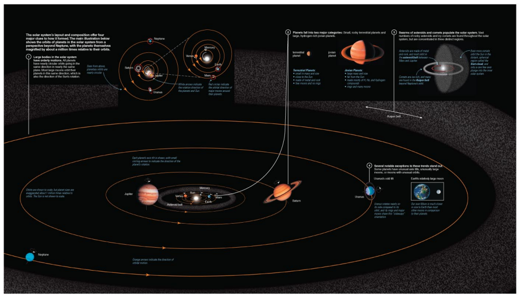
[a]Including the dwarf planets Pluto and Eris; Appendix E gives a more complete list of planetary properties
[b]Surface temperatures for all objects except Jupiter, Saturn, Uranus, and Neptune, for which cloud-top temperatures are listed
[c]Include water (H_2O), methane (CH_4), and ammonia (NH_3)

6.2 The Nebular Theory of Solar System Formation

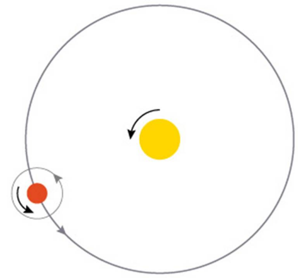
Our goals for learning:

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

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

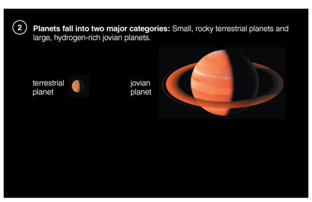


Patterns of Motion Among Large Bodies



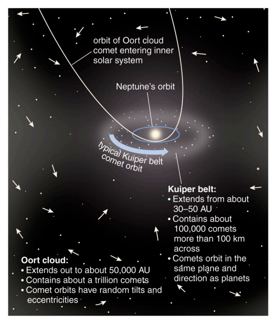
- All large bodies in the solar system orbit in the same direction and in nearly the same plane.
- Most also rotate in that direction.

Two Major Planet Types



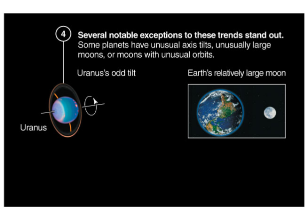
- Terrestrial planets are rocky, relatively small, and close to the Sun.
- Jovian planets are gaseous, larger, and farther from the Sun.

Swarms of Smaller Bodies



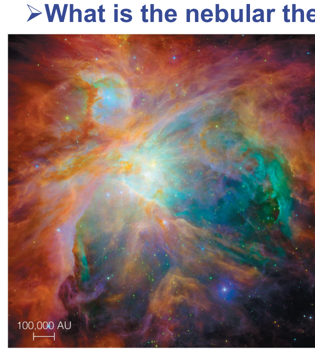
- Many rocky asteroids and icy comets populate the solar system.

Notable Exceptions



- Several exceptions to normal patterns need to be explained.

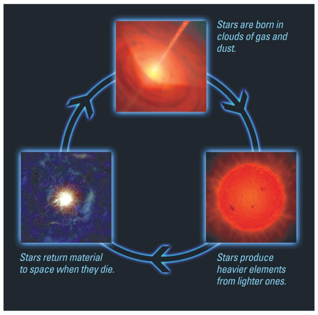
➢What is the nebular theory?



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

(**nebula** = cloud)

Origin of the Nebula



- Elements that formed planets were made in stars and then recycled over generations through interstellar space.
- Despite billions of years of recycling, the universe remains dominantly H/He

Evidence from Other Gas Clouds

MA INTERACTIVE FIGURE

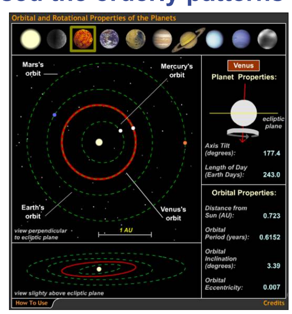
- We can see stars forming in other interstellar gas clouds, lending support to the nebular theory.

6.3 Explaining the Major Features of the Solar System

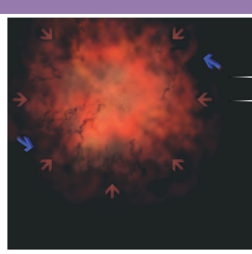
Our goals for learning:

- 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"?

What caused the orderly patterns of motion?

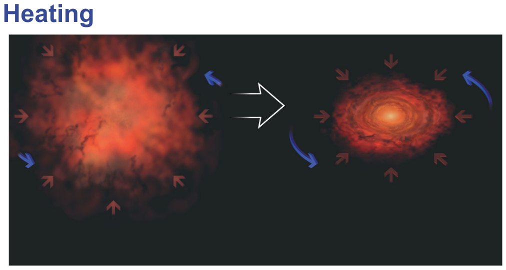


PLAY Orbital and Rotational Properties of the Planets



- Initially gas was spread out; a few light years.
- Cataclysmic events assisted collapse; shock waves
- Eventually gravity pulled inward in all directions

Heating

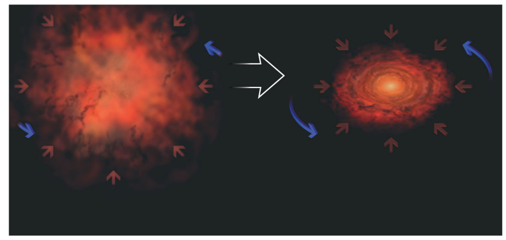


- Conservation of energy
  - Gravitational potential → kinetic → thermal

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

PLAY Collapse of the Solar Nebula

Spinning

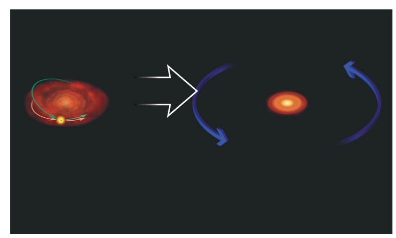


- Conservation of angular momentum
  - The rotational speed of the cloud increased as the cloud contracted.

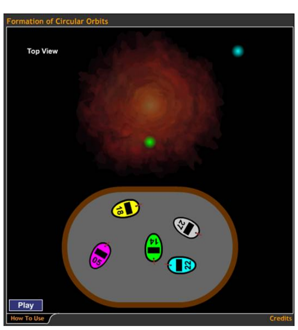
Rotation of a contracting cloud speeds up for the same reason a skater speeds up as she pulls in her arms.

PLAY Collapse of the Solar Nebula

Flattening

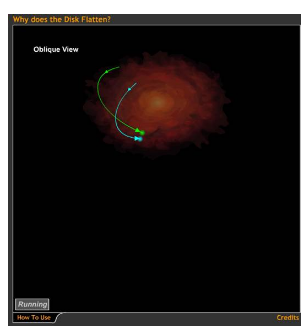


- Collisions between particles caused it to flatten into a disk.
  - Clumps collide and merge with average velocity
  - Collisions between highly elliptical orbits reduce eccentricities
  - Thus, random motions become more orderly



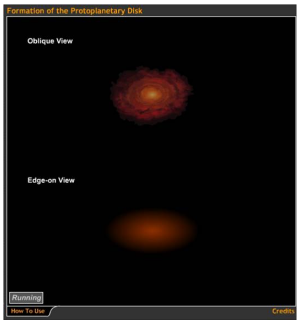
Collisions between gas particles in a cloud gradually reduce random motions.

PLAY Formation of Circular Orbits



Collisions between gas particles also reduce up and down motions.

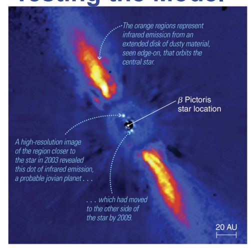
PLAY Why Does the Disk Flatten?



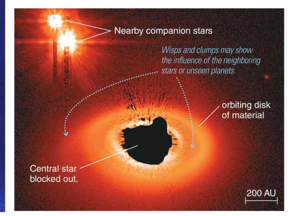
Explains:
- Planets orbit the Sun on the ecliptic plane
- Direction of the Sun's rotation and orbits of planets
- Orbits of the planets are nearly circular

PLAY Formation of the Protoplanetary Disk

Testing the Model



a This infrared image composite from the European Southern Observatory shows a large debris disk orbiting the star Beta Pictoris and a probable jovian planet that has formed from the disk. Images were taken with the star itself blocked; the star's position has been added digitally.



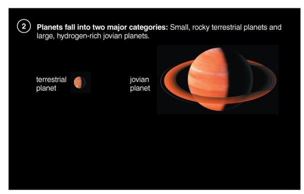
b This Hubble Space Telescope photo shows a disk around the star HD141569A. The colors are not real; a black-and-white image has been tinted red to bring out faint detail.

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

Recap

- What caused the orderly patterns of motion?
  - The solar nebula spun faster as it contracted because of conservation of angular momentum.
  - Collisions between gas particles then caused the nebula to flatten into a disk.
  - We have observed such disks around newly forming stars.

➢Why are there two major types of planets?



- The solar nebula should have had the same composition throughout.
- Why then are planets so different?
  - Key is location

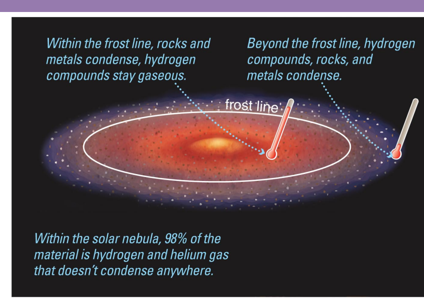
Condensation: Sowing the seeds of planets

- Terrestrials formed in the warm inner region. Jovians formed in the colder outer region.
- When temperature is low enough some atoms and molecules in gas may bond and solidify.

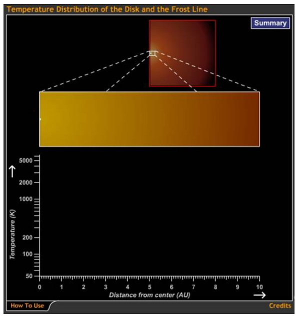
TABLE 6.3 Materials in the Solar Nebula

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	Typical condensation temperature	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%



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

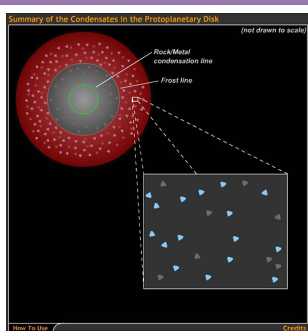


- Inner parts of the disk are hotter than outer parts.
- Rock can be solid at much higher temperatures than ice.

PLAY Temperature Distribution of the Disk and the Frost Line

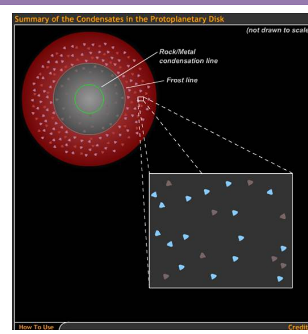
Formation of Terrestrial Planets

- 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.



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

PLAY Summary of the Condensates in the Protoplanetary Disk



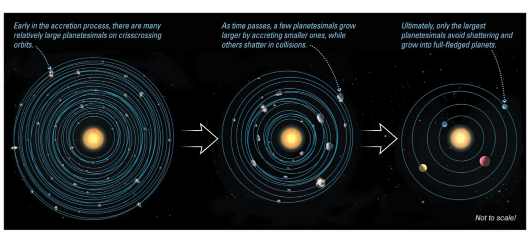
Gravity draws ***planetesimals*** together to form planets.

This process of assembly

is called ***accretion.***

PLAY Summary of the Condensates in the Protoplanetary Disk

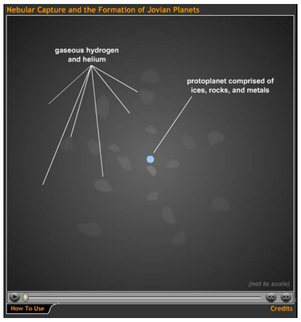
Accretion of Planetesimals



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

Formation of Jovian Planets

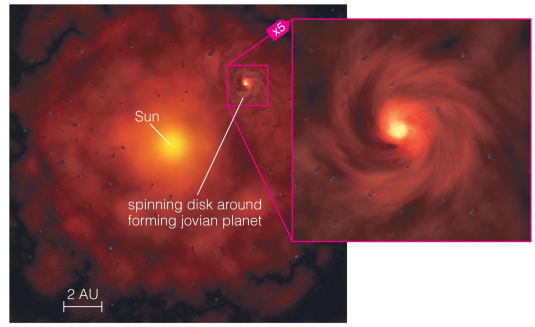
- Ice could also form small particles outside the frost line.
- Larger planetesimals and planets were able to form.
- The gravity of these larger planets was able to draw in surrounding H and He gases.



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

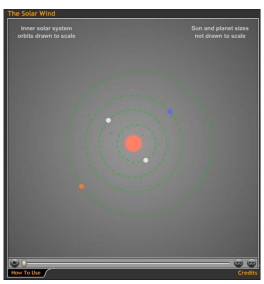
Eventually, they accreted so much gas they bore little resemblance to the icy seed.

PLAY Nebular Capture and the Formation of the Jovian Planets



- Moons of jovian planets form in miniature disks.

Clearing the Nebula



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

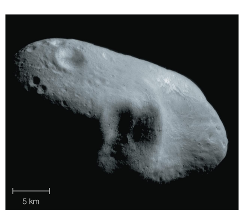
Had the gases remained, it could have cooled until hydrogen compounds condensed.

PLAY The Solar Wind

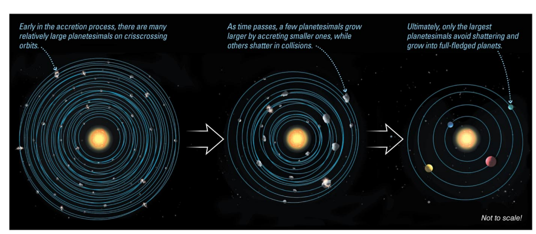
Recap

- Why are there two major types of planets?
  - Rock, metals, and ices condensed outside the frost line, but only rock and metals condensed inside the frost line.
  - Small solid particles collected into planetesimals that then accreted into planets.
  - Planets inside the frost line were made of rock and metals.
  - Additional ice particles outside the frost line made planets there more massive, and the gravity of these massive planets drew in H and He gases.

➢Where did asteroids and comets come from?

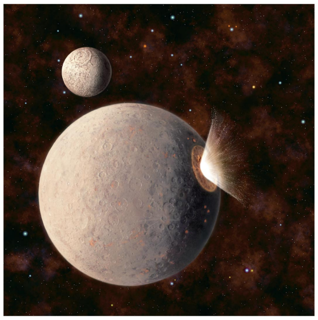


Asteroids and Comets



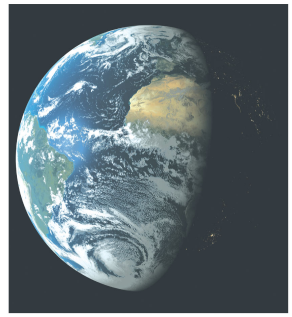
- Leftovers from the accretion process
- Rocky asteroids inside frost line
- Icy comets outside frost line

Heavy Bombardment



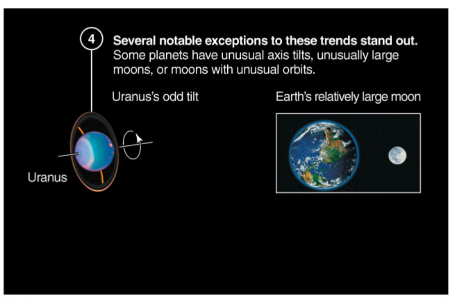
- Leftover planetesimals bombarded other objects in the late stages of solar system formation.

Origin of Earth's Water

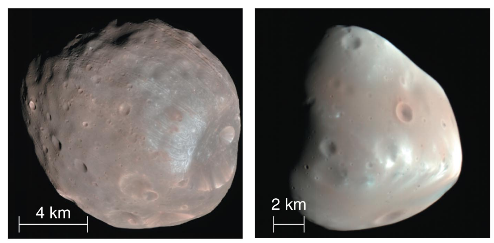


- Water may have come to Earth by way of icy planetesimals from the outer solar system.

➢How do we explain "exceptions to the rules"?



Captured Moons



a Phobos **b** Deimos

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

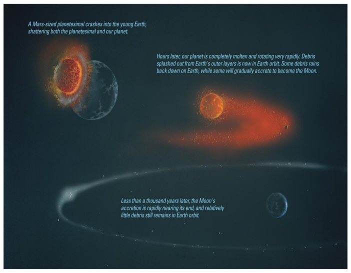
Not easy to capture a moon

- Objects cannot switch from an unbound orbit.
- Lost energy to friction in dense gas surrounding these planets
- Due to random nature of capture
  - Moons may not orbit in same direction
  - Moons may not orbit in equatorial plane
- Most small moons of Jovian planets were captured in this way

Giant Impact Formation of Our Moon

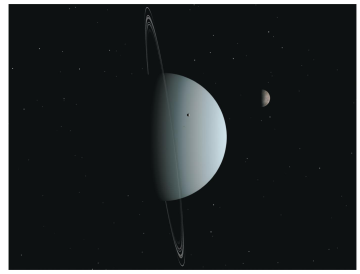
- Our Moon is to large to be captured
- We can rule out that they formed simultaneously or they would have accreted from planetesimals of similar composition and density
- Result from giant impact between Earth and huge planetesimal
  - Giant impact blasted Earth's outer layers into orbit
  - Then accreted into the Moon

Giant Impact



- ❑Simulations indicate Mars size planetesimals.
- ❑Moons over all composition is similar to Earth's outer layers.
- ❑Moon has smaller proportions of easily vaporized ingredients (water).

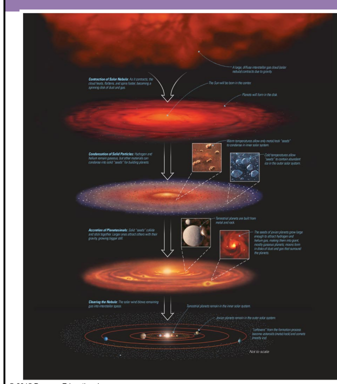
Other Exceptions



- ❑ Giant impacts might also explain the odd rotation axes of some planets.
- ❑ Perhaps Venus's slow backward rotation.

Recap

- ❑Where did asteroids and comets come from?
  - They are leftover planetesimals, according to the nebular theory.
- ❑How do we explain "exceptions to the rules"?
  - The bombardment of newly formed planets by planetesimals may explain the exceptions.
  - Material torn from Earth's crust by a giant impact formed the Moon.



- ❑Recap of the nebular theory
  - Contraction
  - Condensation
  - Accretion
  - Clearing

6.4 The Age of the Solar System

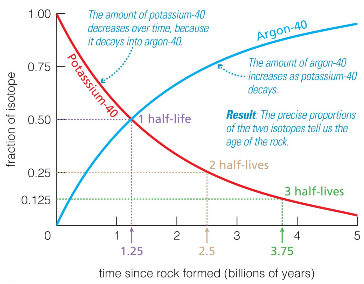
Our goals for learning:

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

➢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.
- ❑ **Radiometric dating** the age of a rock since atoms become locked together, since the last time the rock solidified.

Radioactive Decay



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

Potassium-40 decays
19P & 21N ;1P → 1N
Creates Argon-40

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.

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.