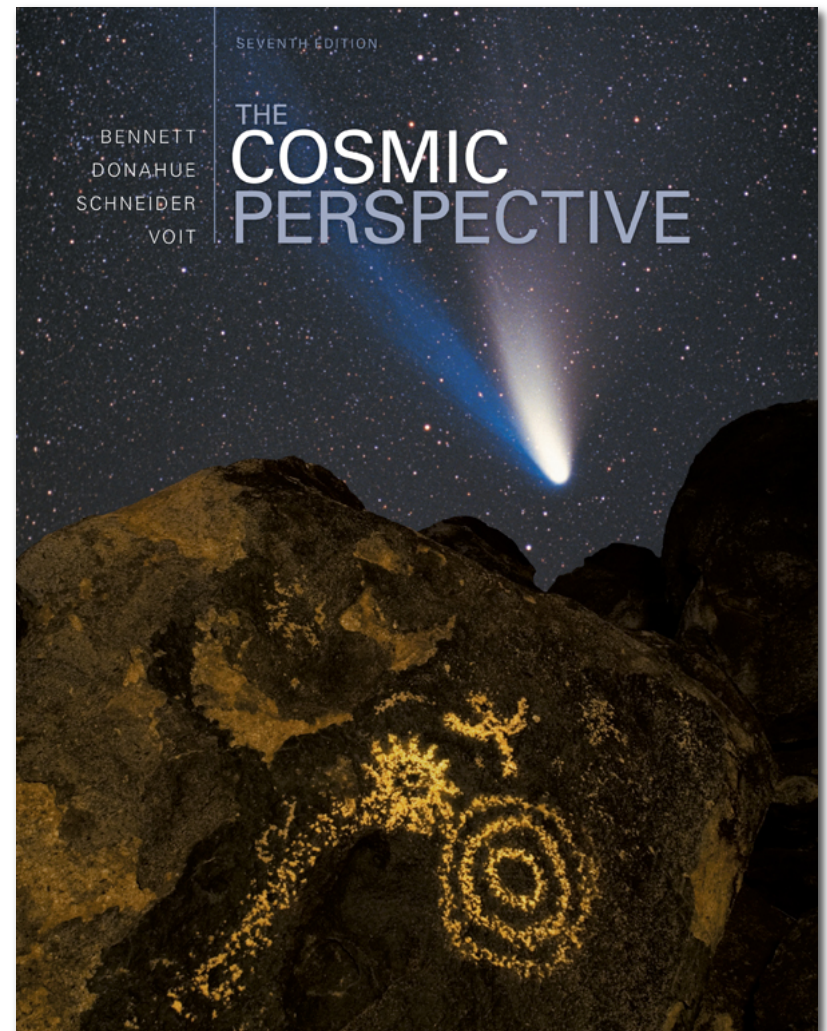


Chapter 8 Lecture

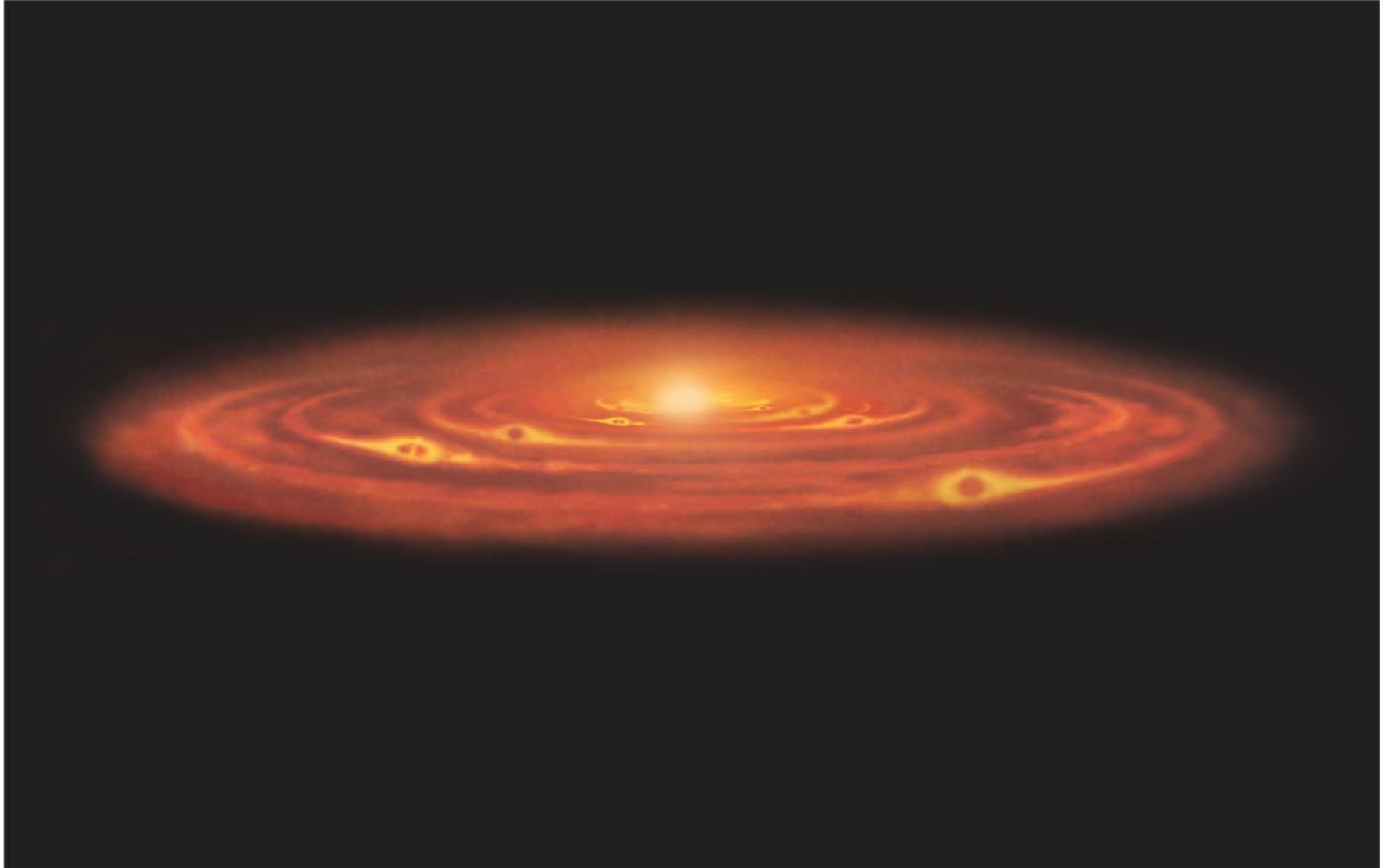
The Cosmic Perspective

Seventh Edition

Formation of the Solar System



Formation of the Solar System



8.1 The Search for Origins

- Our goals for learning:
 - **Develop a theory of solar system formation**
 - **Where did the solar system come from?**

A Theory for the Origin of the Solar System

Present day properties of the solar system that aid us in constructing a theory of the origin of the solar system:

Property 1: The terrestrial planets are composed primarily of hard rocky substances while the Jovian planets are composed primarily of hydrogen and helium.

Property 2: The Jovian planets are significantly larger and massive than the Terrestrial planets.

Property 3: All planets orbit the sun in the same direction and their orbits are near the ecliptic plane.

Property 4: The terrestrial planets orbit significantly closer to the sun than the Jovian planets.

Property 5: Existence of smaller bodies such as asteroids and comets

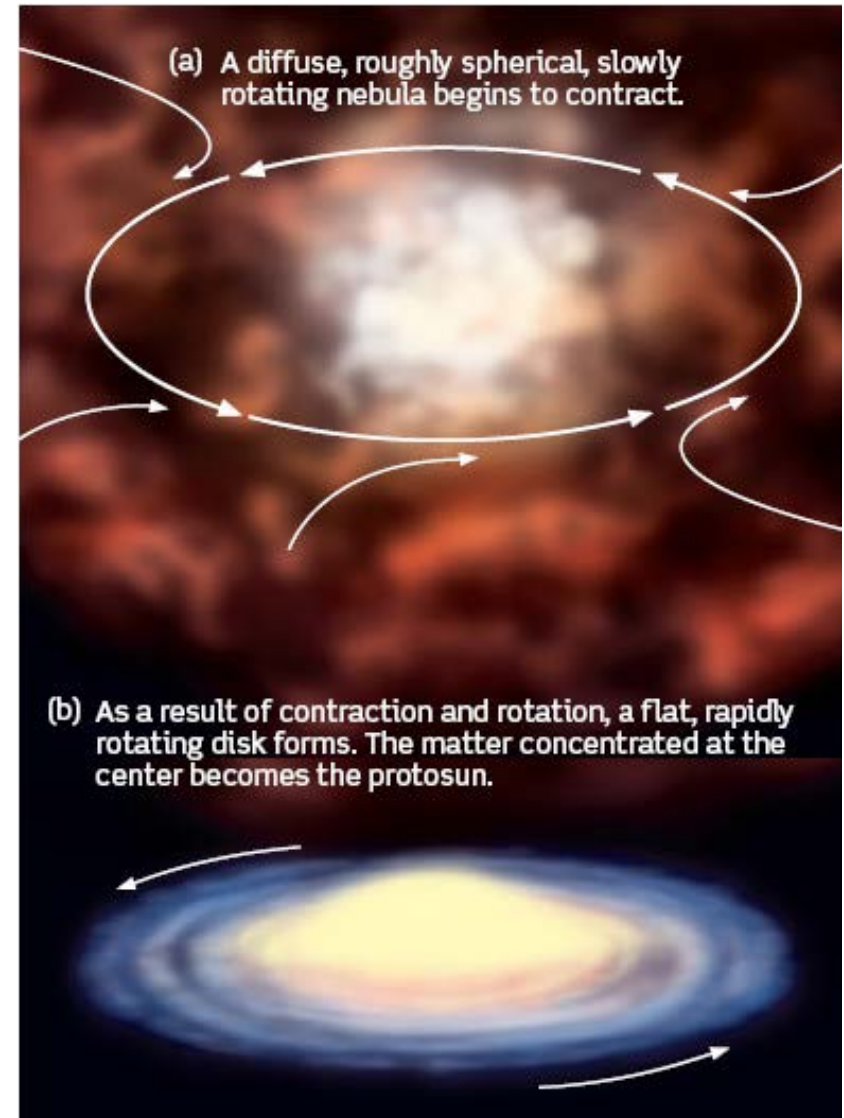
Property 6: Notable exceptions to usual patterns rotation of Uranus, Earth's Moon, etc.

Nebular Hypothesis

The nebular hypothesis states that our solar system formed from the gravitational collapse of a giant interstellar gas cloud—the **solar nebula**

As the cloud flattens and spins more rapidly around its rotation axis, a central condensation develops that evolves into a glowing protosun.

The planets will form out of the surrounding disk of gas and dust.



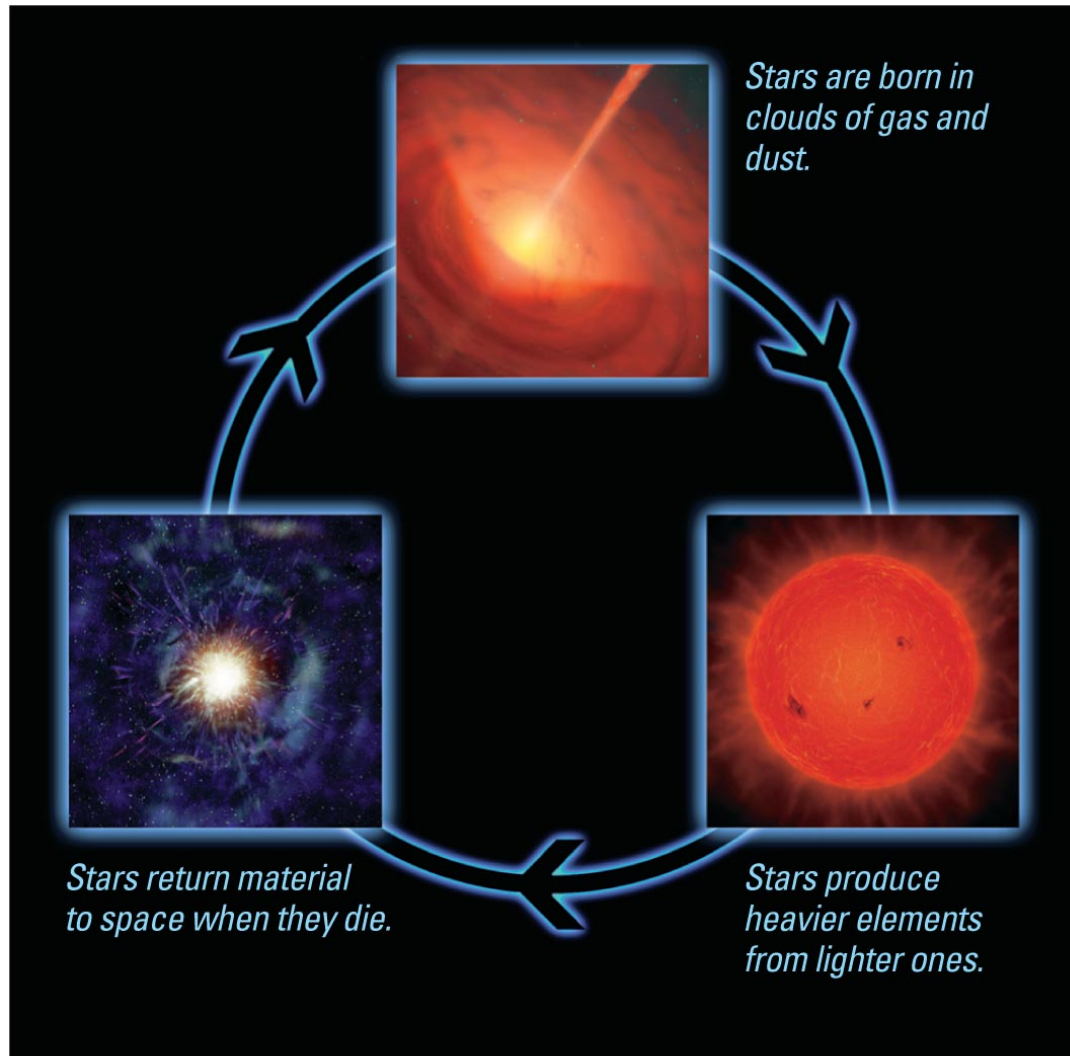
Close Encounter Hypothesis

- A rival idea proposed that the planets formed from debris torn off the Sun by a close encounter with another star.
- That hypothesis could not explain observed motions and types of planets.

Where did the solar system come from?



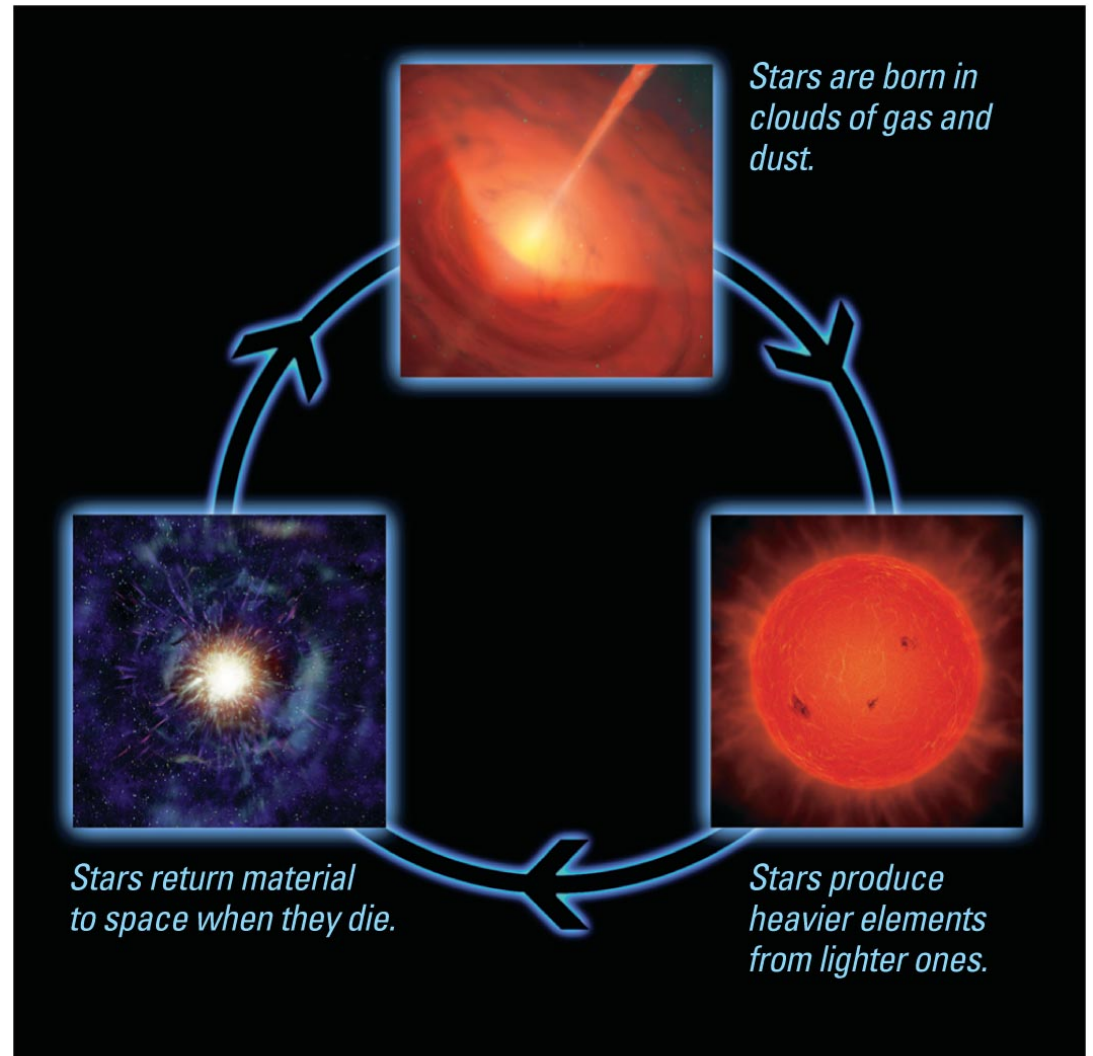
Galactic Recycling



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

Evidence from Other Gas Clouds

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

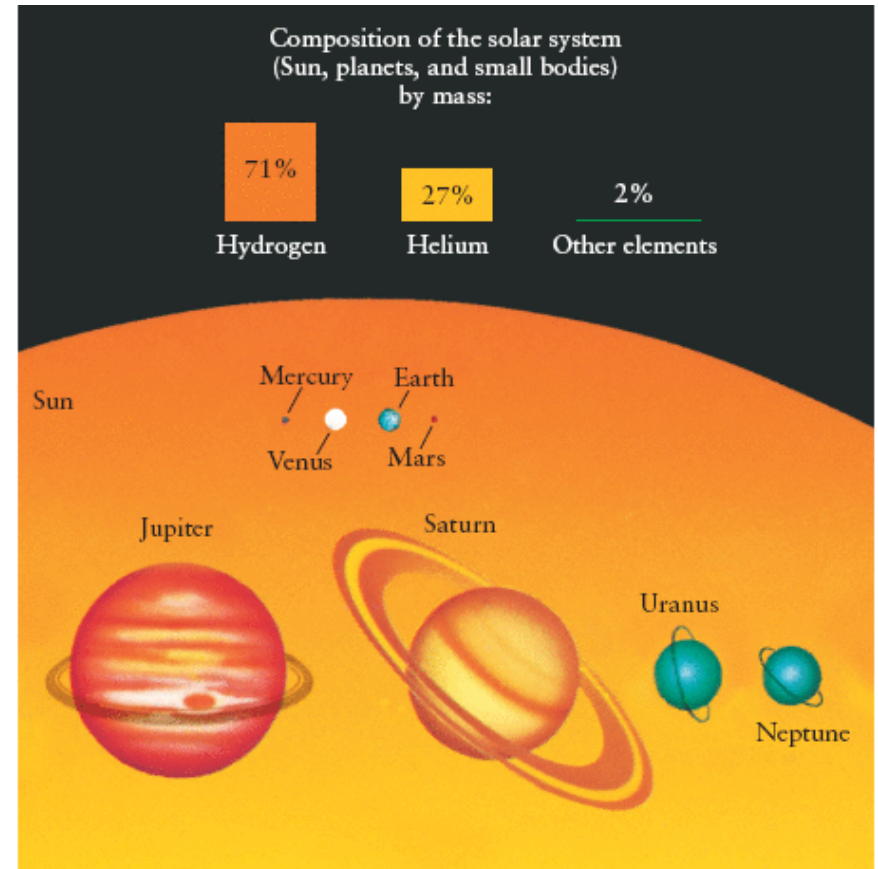


Abundance of Elements in the Solar System

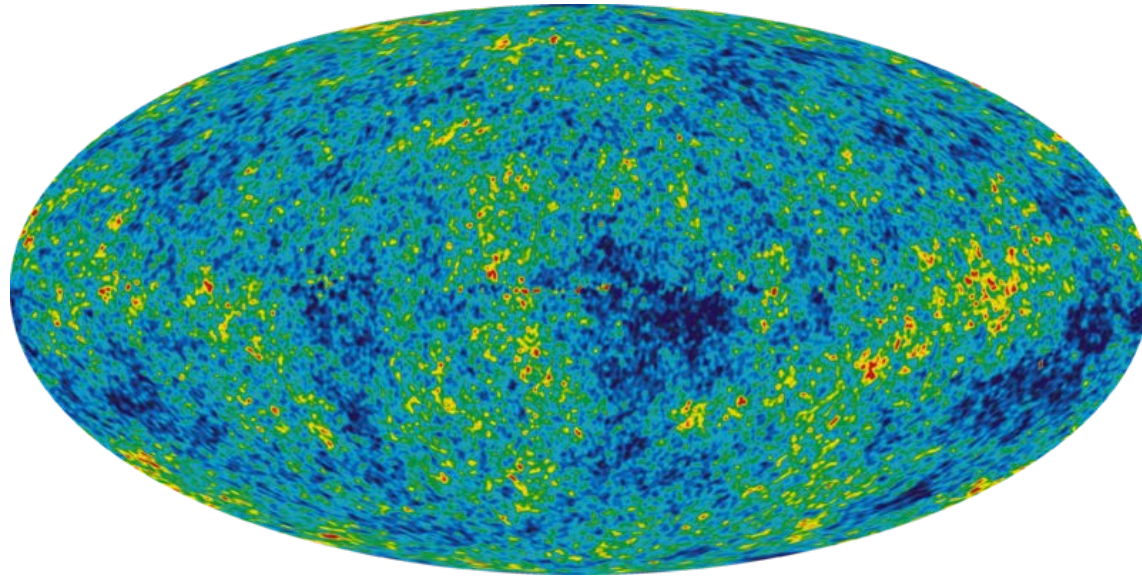
Hydrogen and helium make up almost all of the mass of our solar system. Carbon, oxygen, nitrogen, iron, gold, and uranium constitute only 2% of the total mass.

By analyzing the spectra of stars and galaxies, astronomers have found that most of the visible Universe is composed of hydrogen and helium.

The Terrestrial planets are small because they are made of less abundant elements.



Abundance of Elements in the Universe



Primordial nucleosynthesis took place just a few minutes after the Big Bang and is believed to be responsible for the formation of **Hydrogen and Helium** and of a heavier isotope of hydrogen known as deuterium (H-2 or D), the helium isotopes He-3 and He-4, and the lithium isotopes Li-6 and Li-7.

Heavier elements are manufactured in stars by thermonuclear fusion.

Abundance of Elements in Our Galaxy

Abundances may be quoted **by mass or by number**. Example: Our solar system has 2.6 times more hydrogen than helium by mass, and about 10 times more hydrogen than helium by number. Why? (hint: He-4 = 2 protons + 2 neutrons)

Rare elements: For every 10^{12} hydrogen atoms in the solar system, there are only six atoms of gold. (Today's price for an ounce of gold ~ \$1200)

The reason the terrestrial planets are small is that they are made from heavy and less abundant elements.

What have we learned?

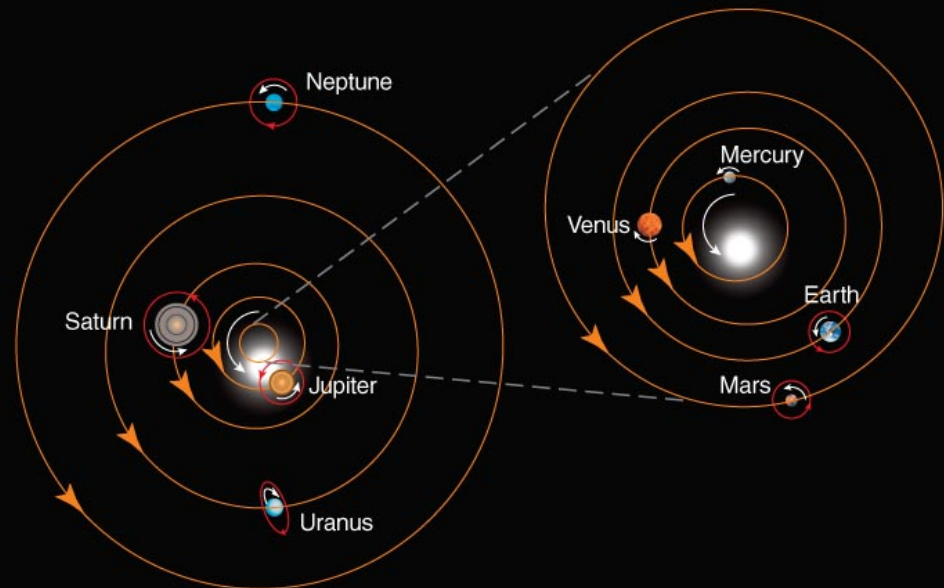
- **How did we arrive at a theory of solar system formation?**
 - Hypotheses arose to explain the major features of the solar system
 - Testing and observation leads from hypothesis to theory.
- **Where did the solar system come from?**
 - The nebular theory states that solar system formed from a large interstellar gas cloud.
 - Galactic recycling built the elements from which planets formed.

8.2 Explaining the Major Features of the Solar System

- Our goals for learning:
 - **What caused the orderly patterns of motion in our solar system?**
 - **Why are there two major types of planets?**
 - **Where did asteroids and comets come from?**
 - **How do we explain "exceptions to the rules"?**

What caused the orderly patterns of motion in our solar system?

- 1 **Large bodies in the solar system have orderly motions.** All planets have nearly circular orbits going in the same direction in nearly the same plane. Most large moons orbit their planets in this same direction, which is also the direction of the Sun's rotation.



Conservation of Angular Momentum



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

Protoplanetary Disk

As the nebular collapses it spins up to **conserve angular momentum**.

The rotation of the nebular leads to a **flattening along the axis of rotation**.

About 100,000 years after the solar nebula first began to contract, it develops a rotating, flattened disk surrounding what will become the **protosun**. This disk is called the **protoplanetary disk or proplyd**.



(a)

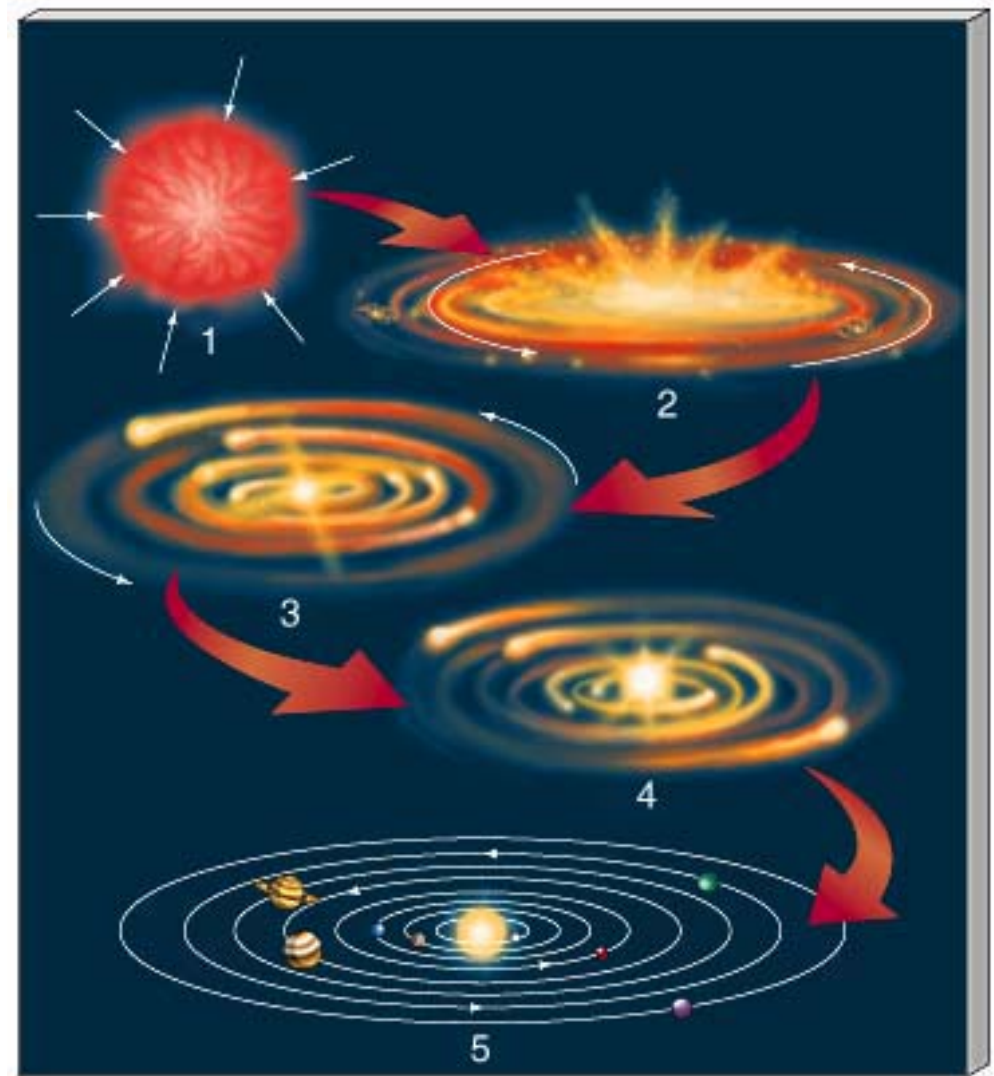


(b)

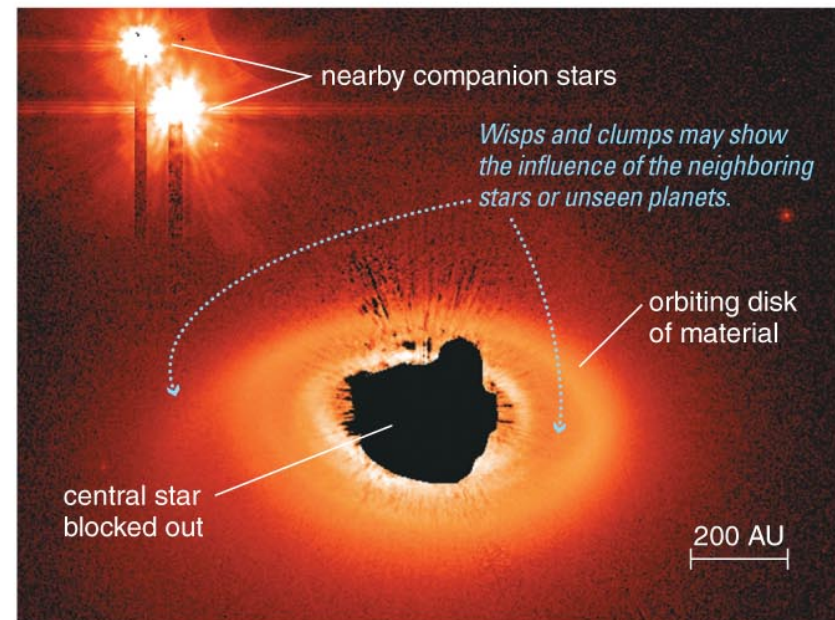
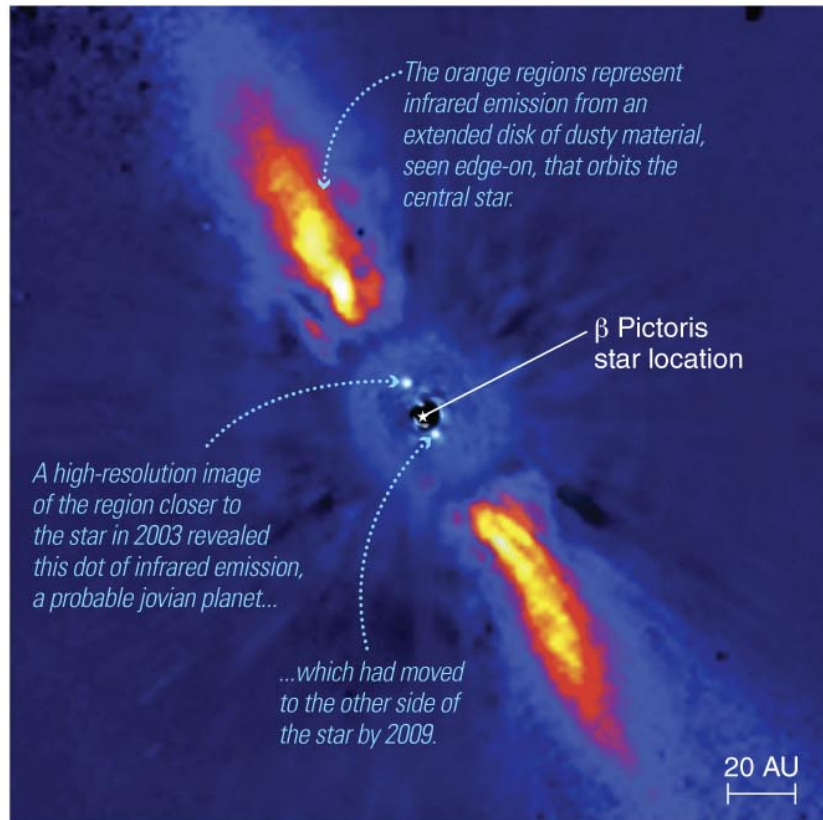
An example of conservation of angular momentum. The spin of the scater increases as she pull her limbs in.

Protoplanetary Disk

- Centripetal force prevents gas from collapsing in the plane of rotation.
- Gas falling from the top collides with gas falling from the bottom and sticks together in the ecliptic plane

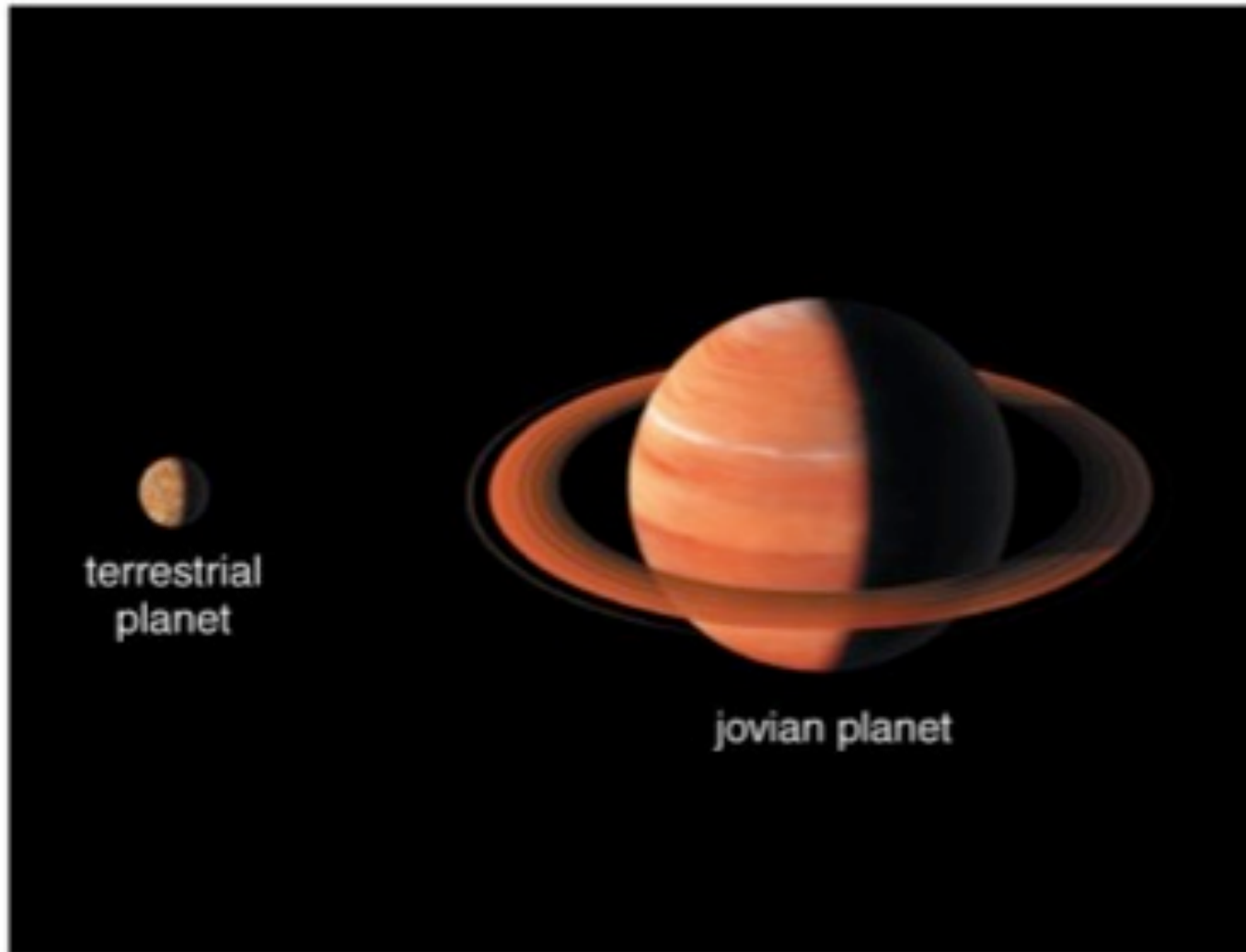


Disks around Other Stars



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

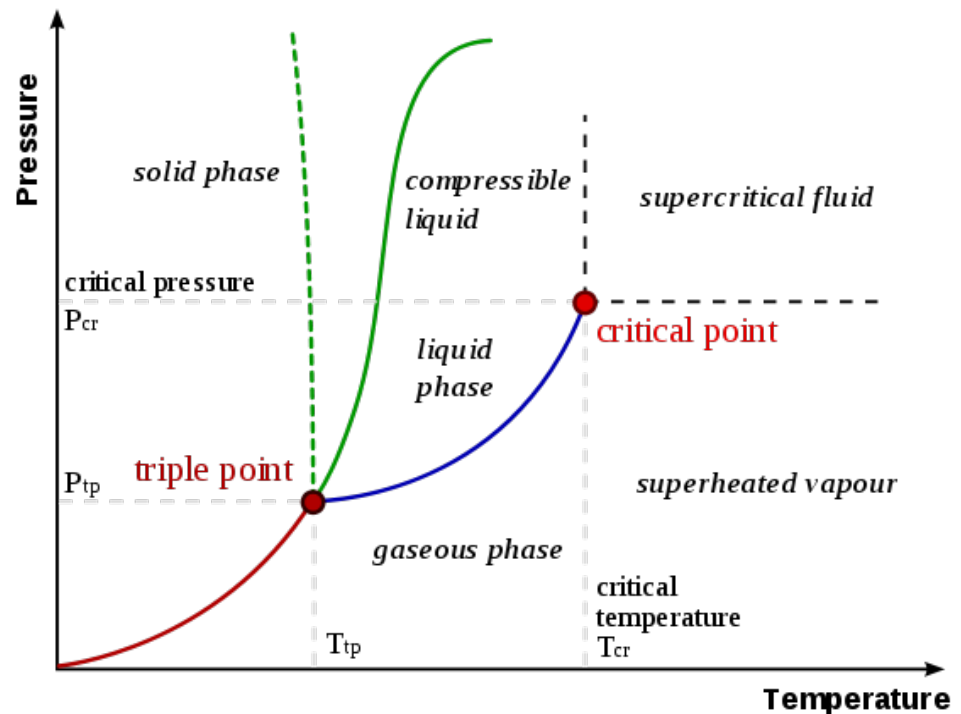
Why are there two major types of planets?



Phase Diagram

Initially the pressure in the solar nebular outside the protostar is very low such that a liquid phase cannot exist.

For very low pressures matter transitions from a gas to a solid phase for temperatures less than the **condensation temperature**.



Condensation Temperature

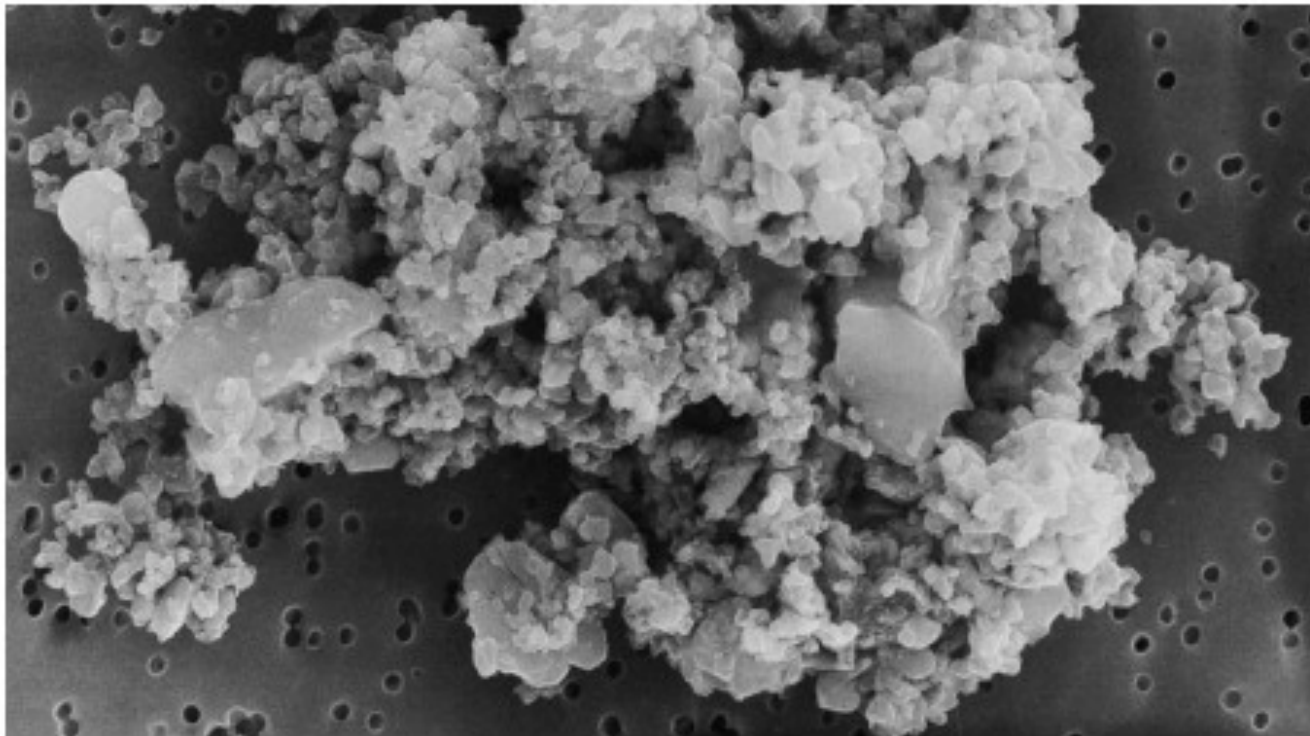
Substances such as water (H_2O), methane (CH_4), and ammonia (NH_3) have low condensation temperatures, ranging from 100 to 300 K.

Rock-forming substances have much higher condensation temperatures, in the range from 1300 to 1600 K.



Sewer top desublimation
(photo by Rob Sheridan)

Dust Grains



10 μm = 0.01 mm

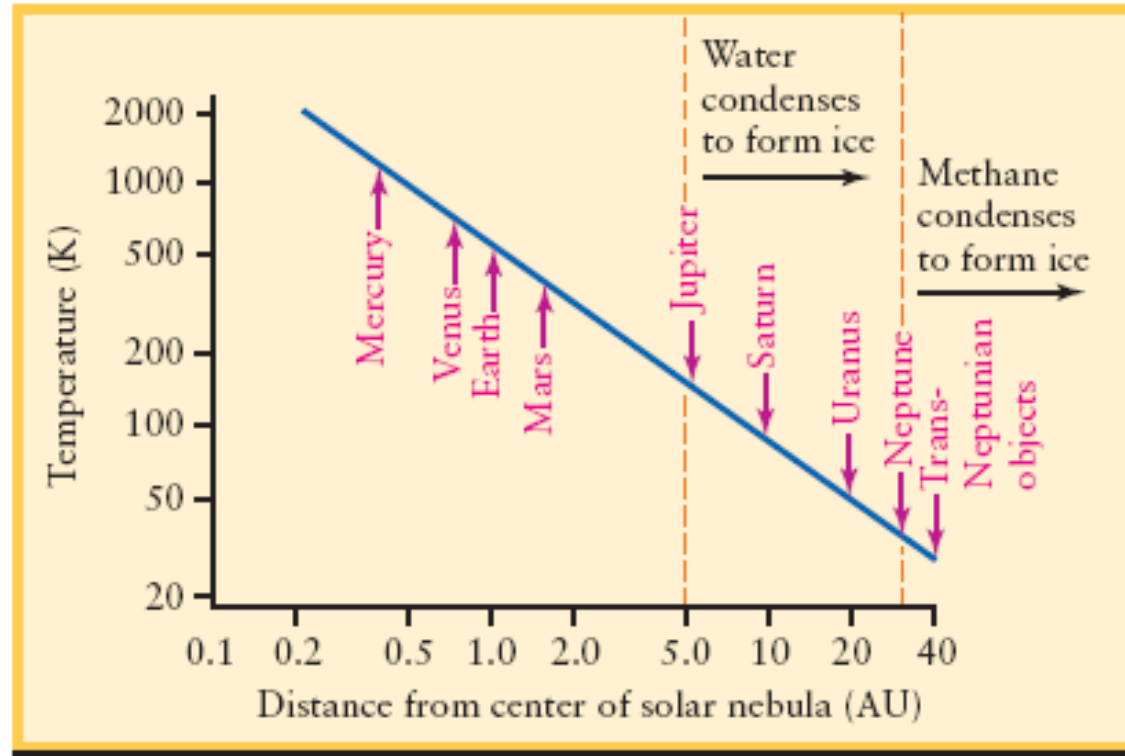
The initial temperature of the solar nebula is thought to have been ~ 50 K so most elements were in the solid phase and formed into small dust grains. These are the building blocks of planets.

Conservation of Energy



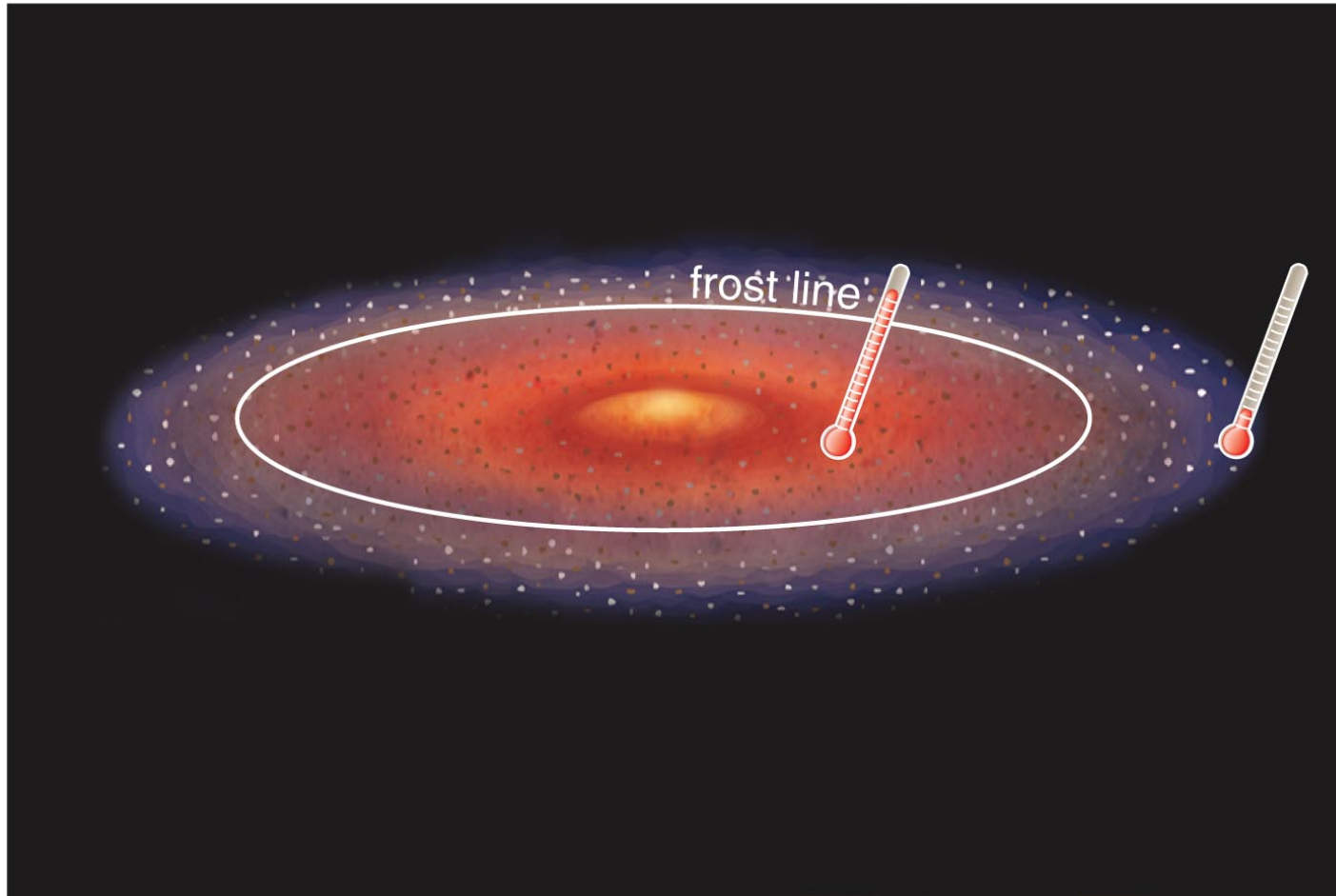
- As gravity causes cloud to contract, it heats up.

Temperature Distribution in Solar Nebular



This graph shows how temperatures probably varied across the solar nebula as the planets were forming. Beyond 5 AU from the center of the nebula (frost line), temperatures were low enough for water to condense and form ice; beyond 30 AU, methane (CH_4) could also condense into ice.

Conservation of Energy



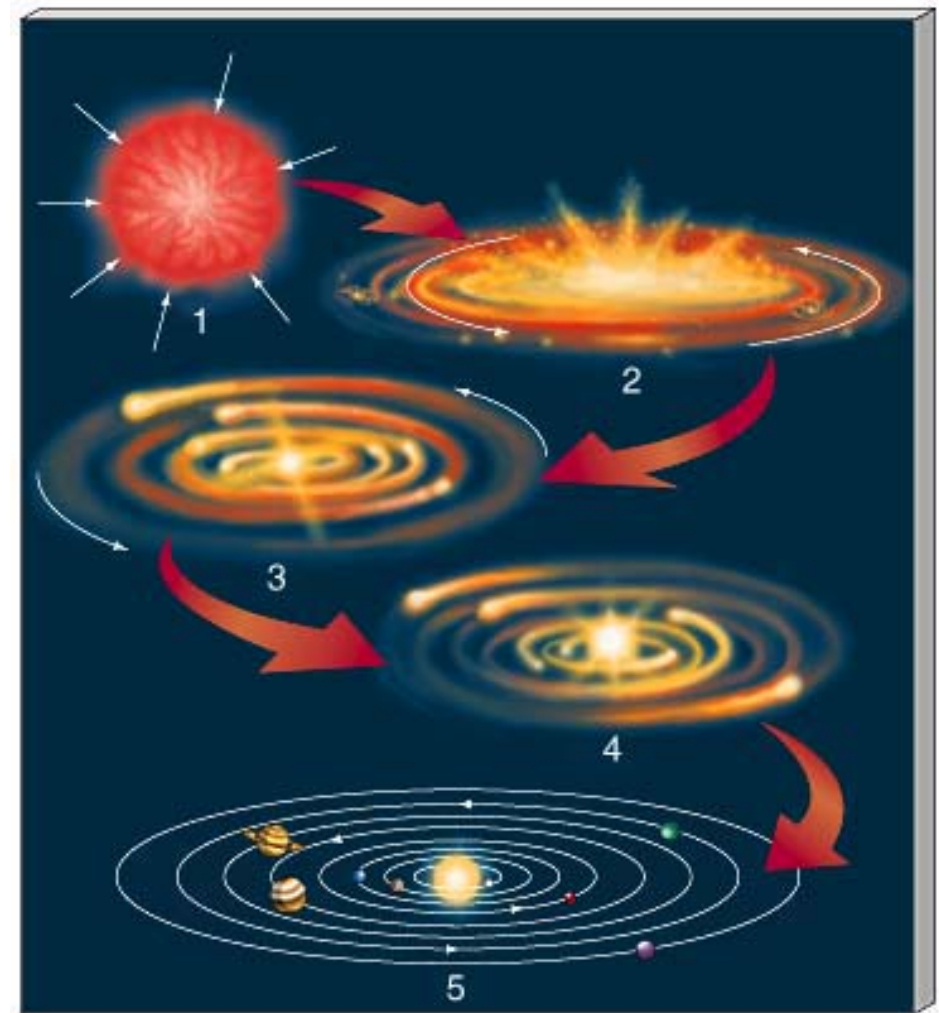
- Inside the ***frost line***: too hot for hydrogen compounds to form ices
- Outside the ***frost line***: cold enough for ices to form

How did the terrestrial planets form?

With time ($\sim 10^6$ years) the dust grains collide and merge into planetesimals (sizes $\sim 1\text{km}$).

Differential rotation (due to Kepler's laws) cause planetesimals in similar orbits to meet up.

They stick together forming a bigger body. The bigger the body, the greater its gravity, and the more attraction it has for other bodies. Protoplanets form.

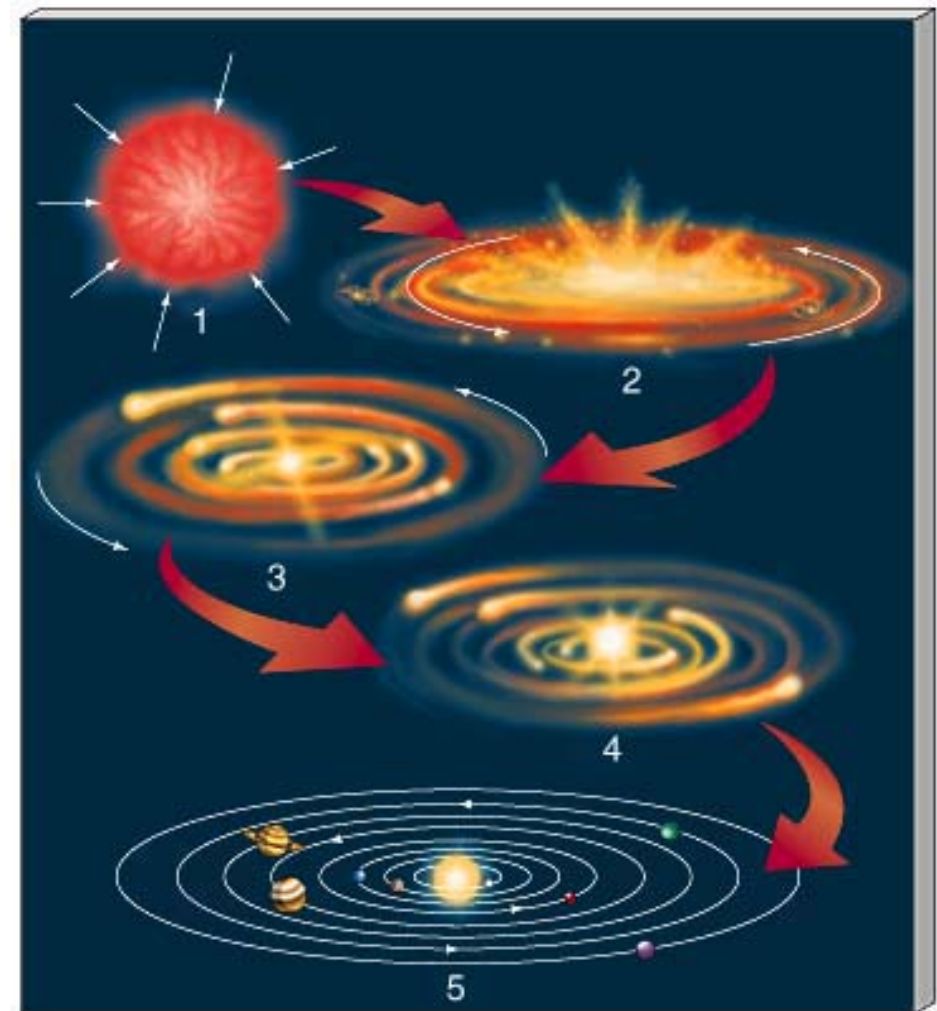


How did the terrestrial planets form?

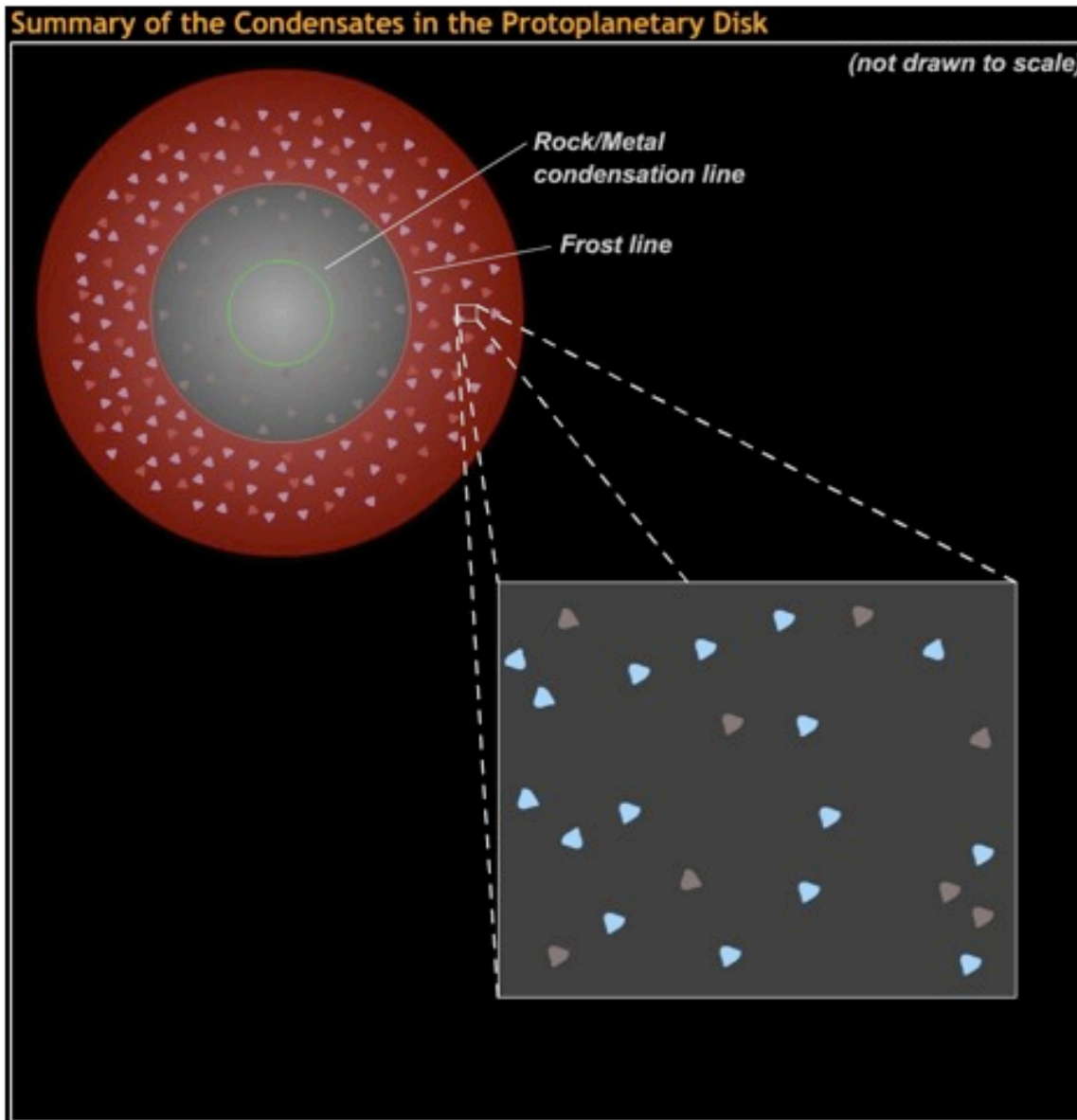
The temperatures **from 0.3-5 AU** were so high in the the solar nebular that **only heavy elements like iron, silicon, magnesium and nickel could be solid.**

This means the protoplanets that formed near the protosun were made out of heavy elements.

Since heavy elements are rare these inner protoplanets were of low mass and therefore could not capture H and He in their atmospheres.

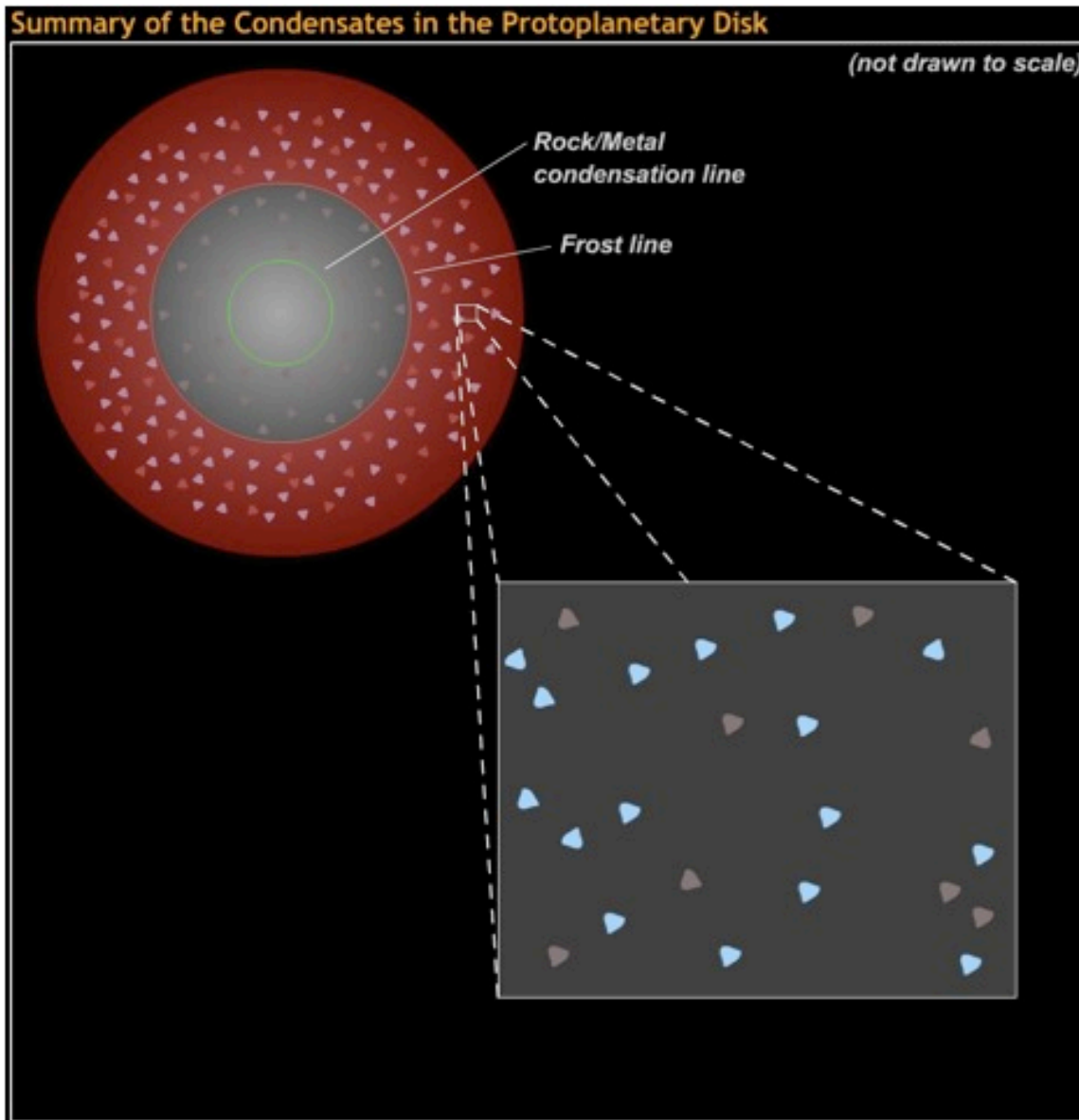


How did the terrestrial planets form?



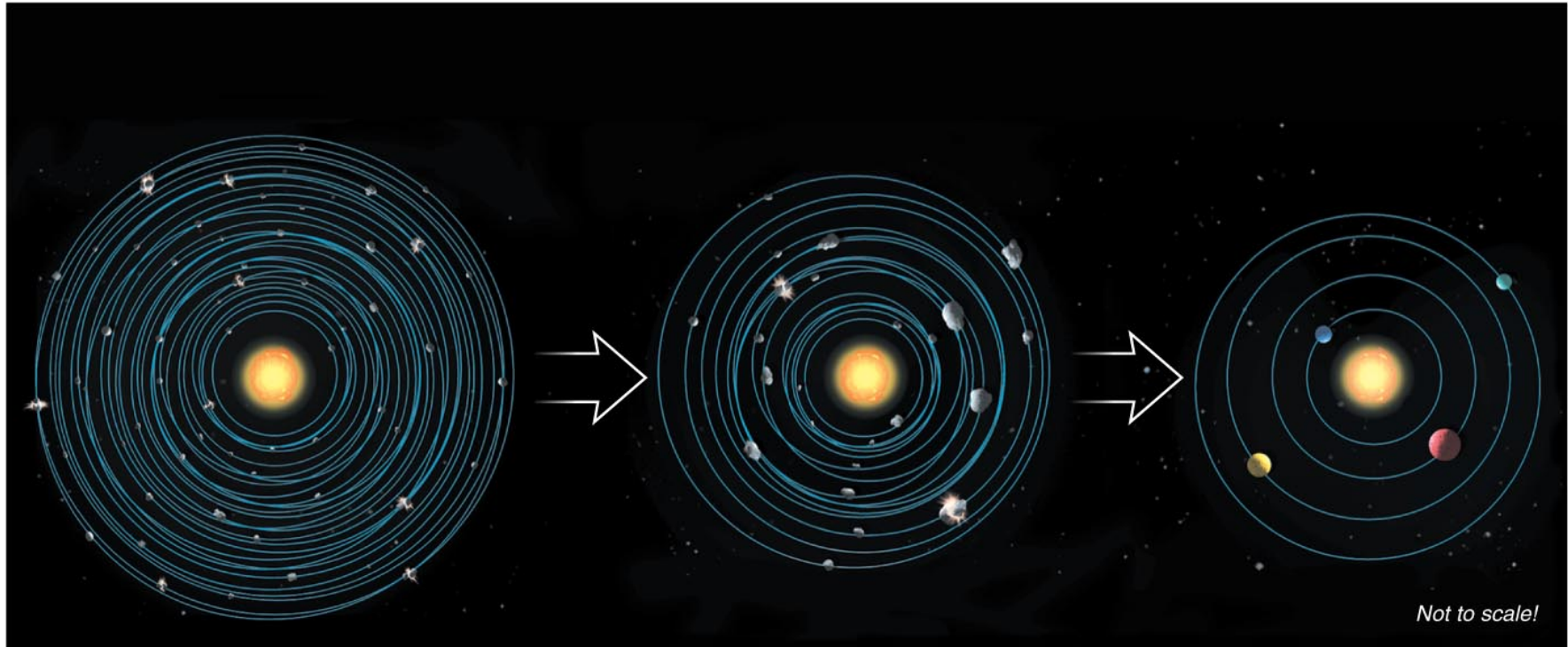
- Tiny solid particles stick to form ***planetesimals***.

How did the terrestrial planets form?



- Gravity draws *planetesimals* together to form planets.
- This process of assembly is called *accretion*.

Accretion of Planetesimals



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

How did the jovian planets form?

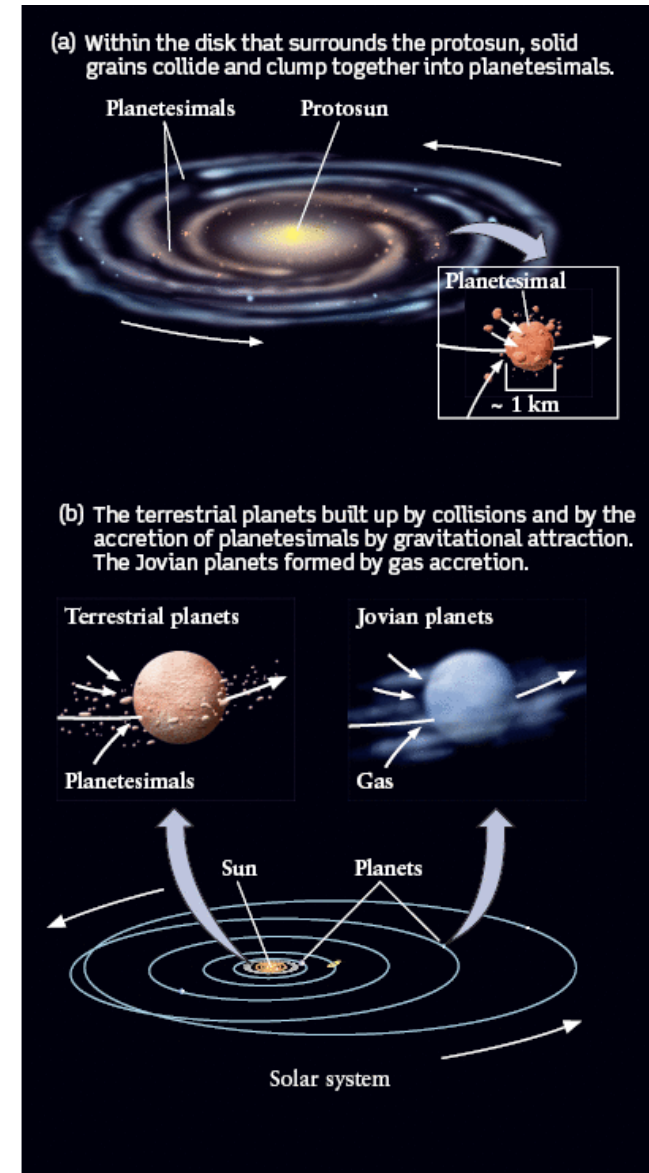
- Ice could also form small particles outside the frost line.
- Larger planetesimals and planets were able to form.
- Gravity of these larger planets was able to draw in surrounding H and He gases.

How did the jovian planets form?

Core Accretion Model

-Begin with the accretion of ice (water, methane, ammonia...) and dust grains to form planetesimals.

-The elements out of which ices are made are more abundant than those of rocky grains thus more matter would have been available for the formation of planetesimals in the outer solar nebular.

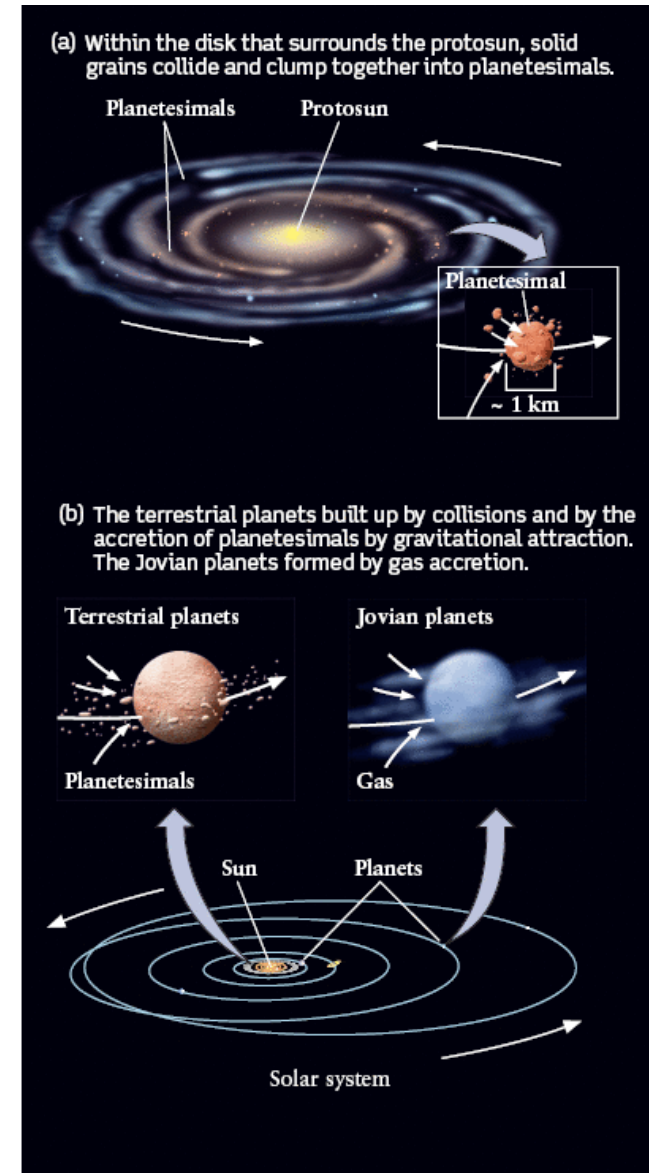


How did the jovian planets form?

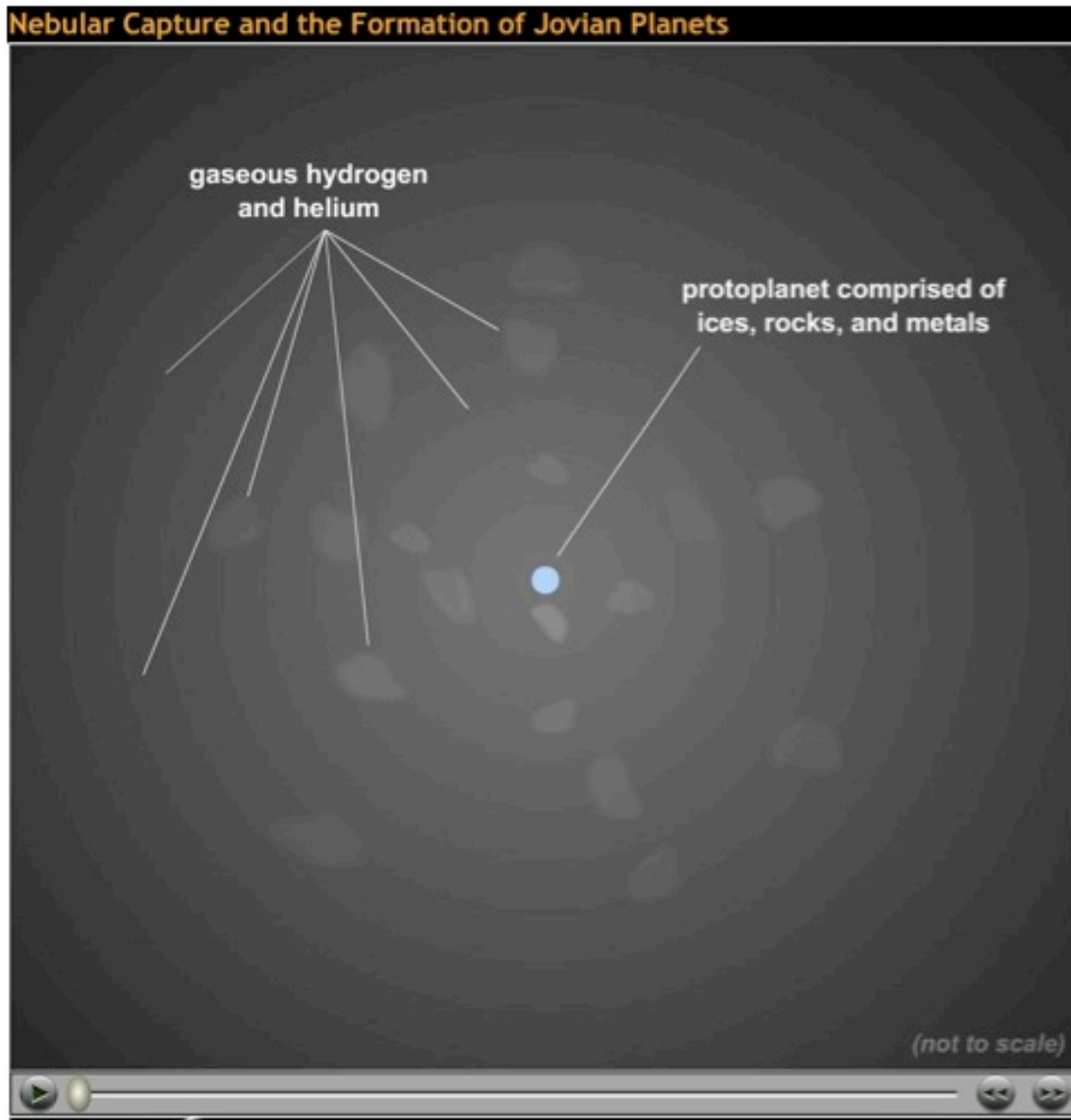
Core Accretion Model

- the planetesimals in the outer solar nebular were more massive than the inner ones thus would have exerted a stronger gravitational force on H and He atoms.

- The lower temperatures of the outer solar nebular resulted in lower average velocities for the H and He atoms and thus these atoms were more easily captured in this region.

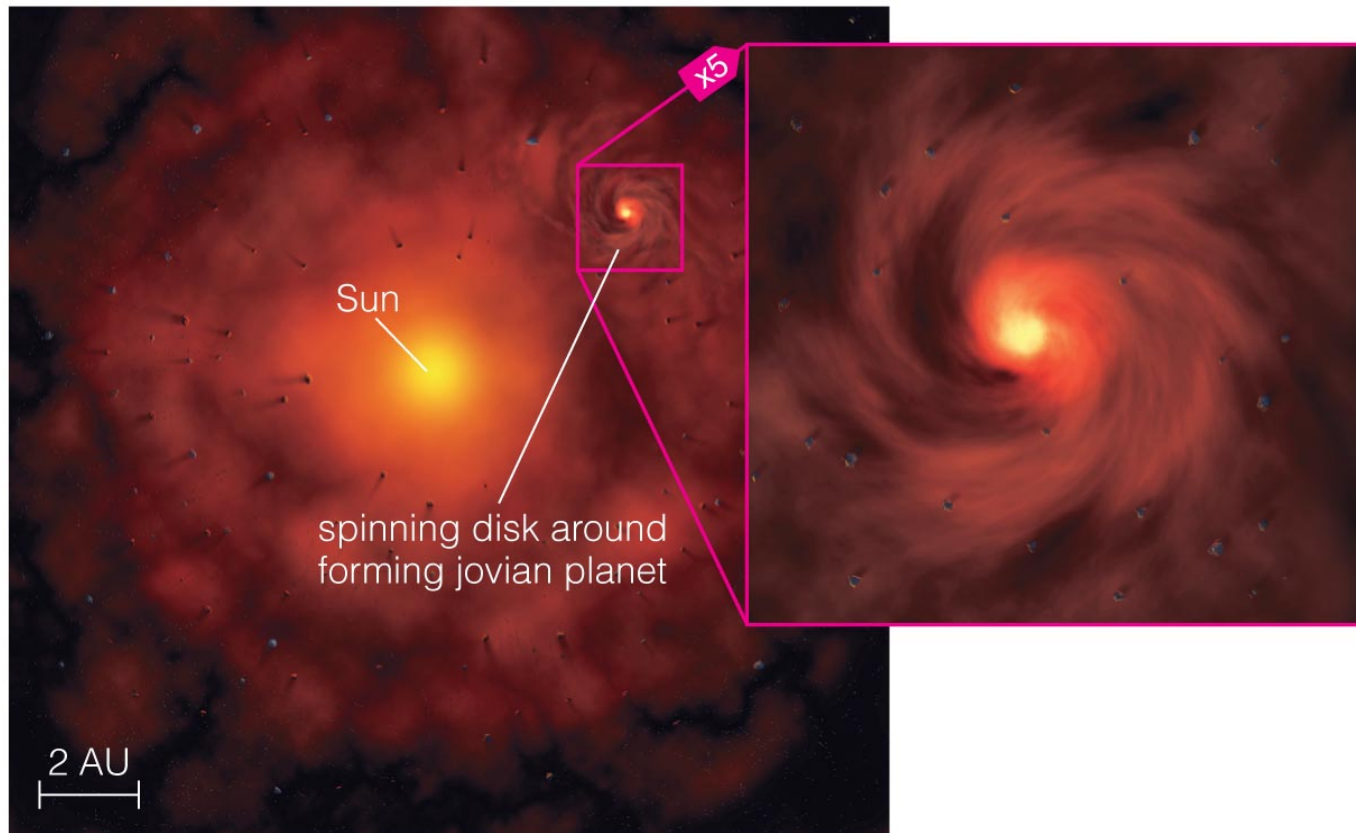


How did the jovian planets form?



- Gravity of rock and ice in jovian planets draws in H and He gases.

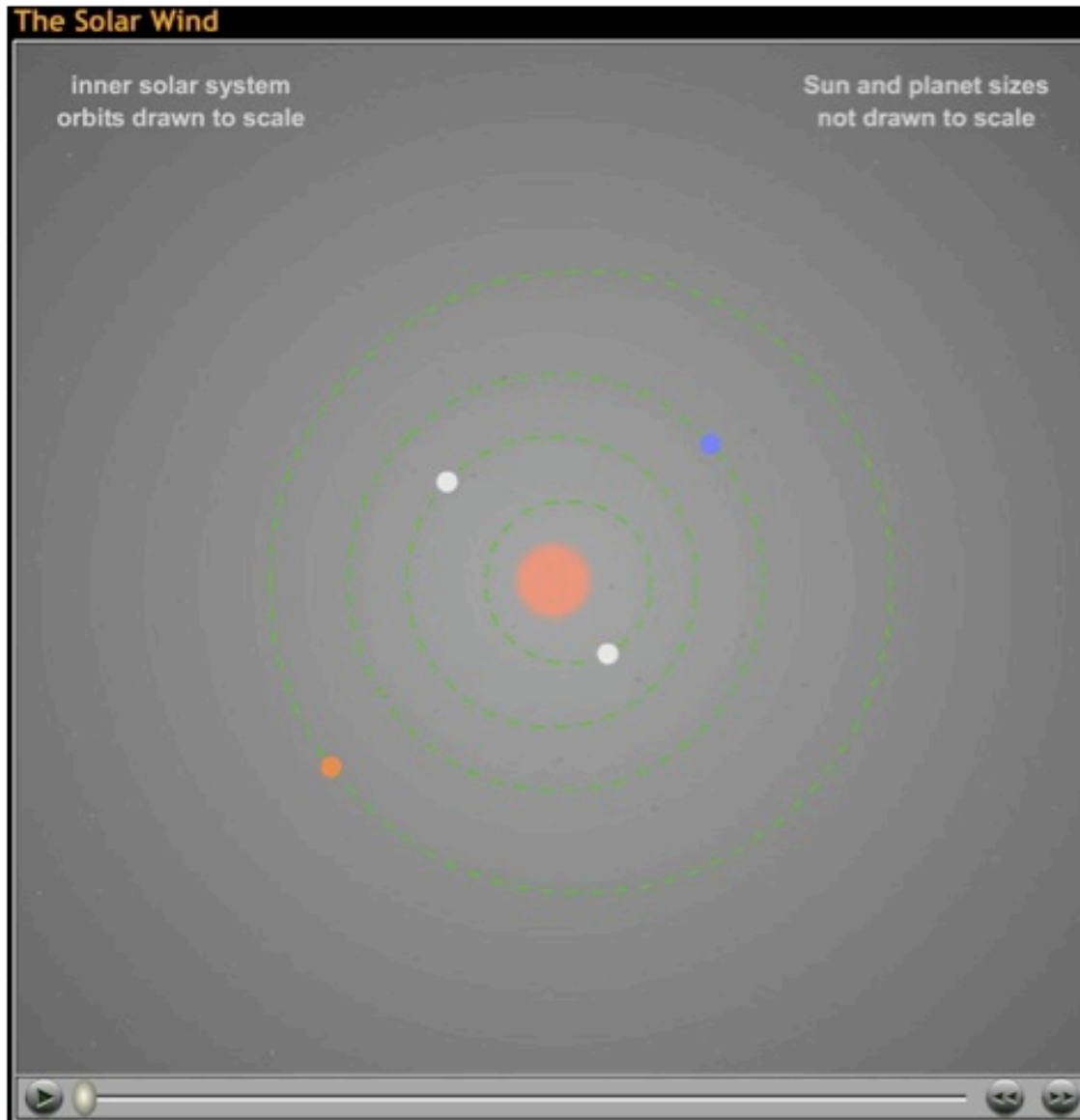
How did the jovian moons form?



As the Jovian planets cooled they formed outer disks, just like the solar nebula in miniature.

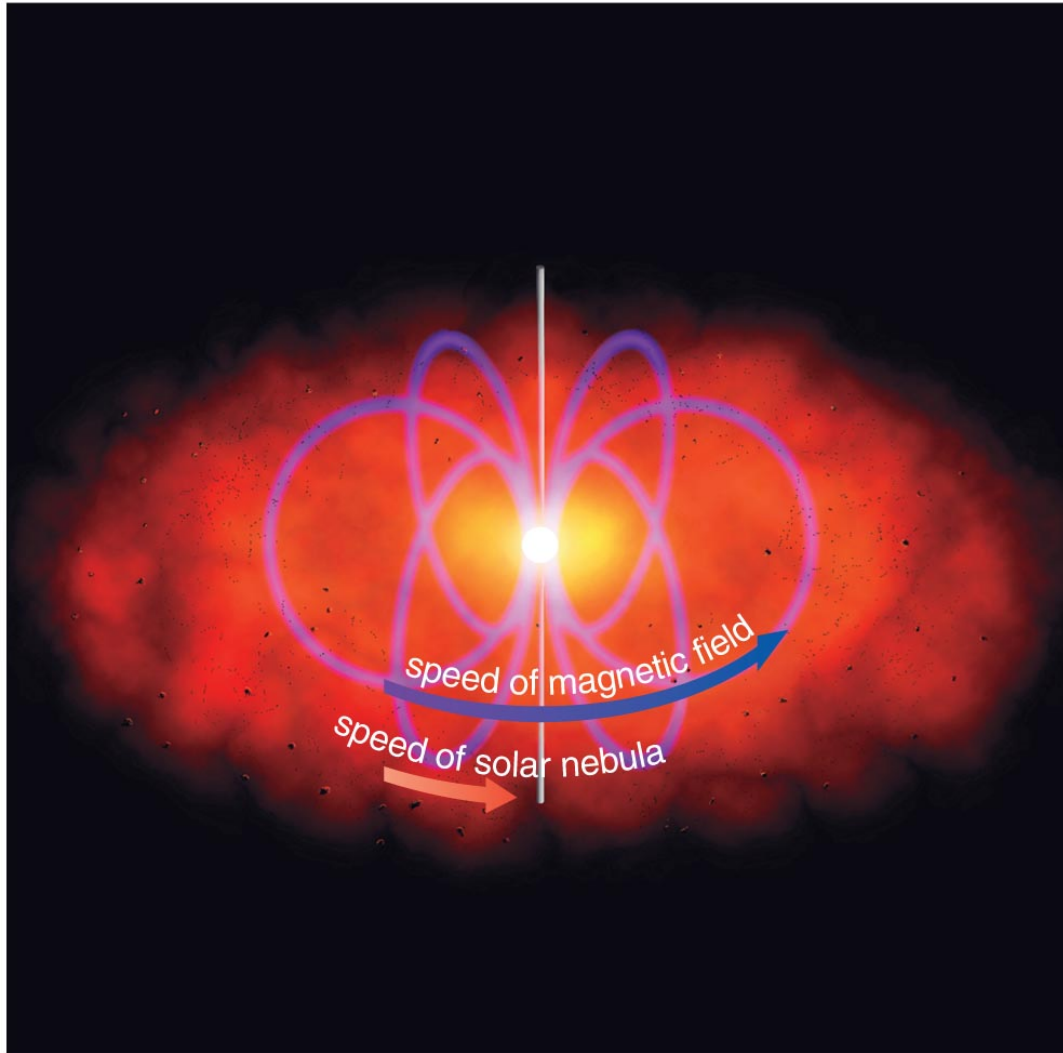
Most of the moons of the Jovian planets are thought to have formed from these disks of ice and dust grains.

What happened to the left over gas?



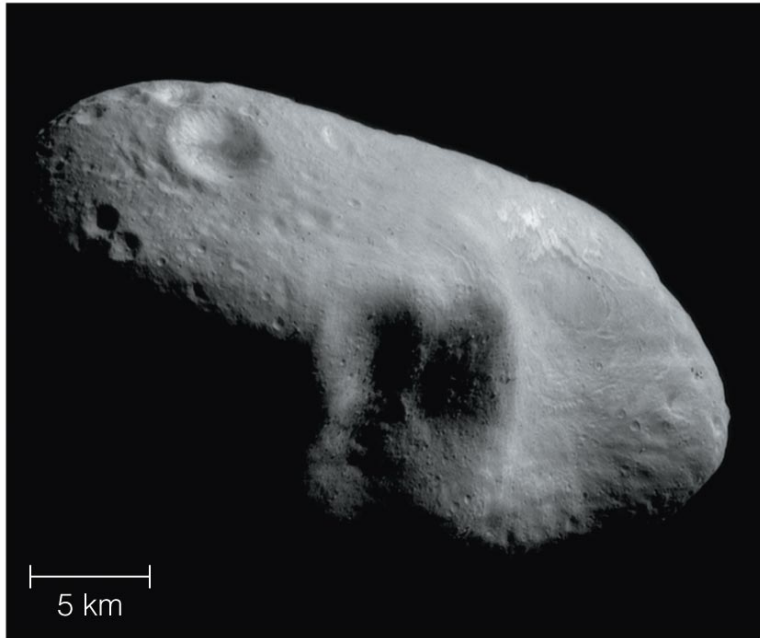
- A combination of photons and the ***solar wind***—outflowing matter from the Sun—blew away the leftover gases.

Solar Rotation

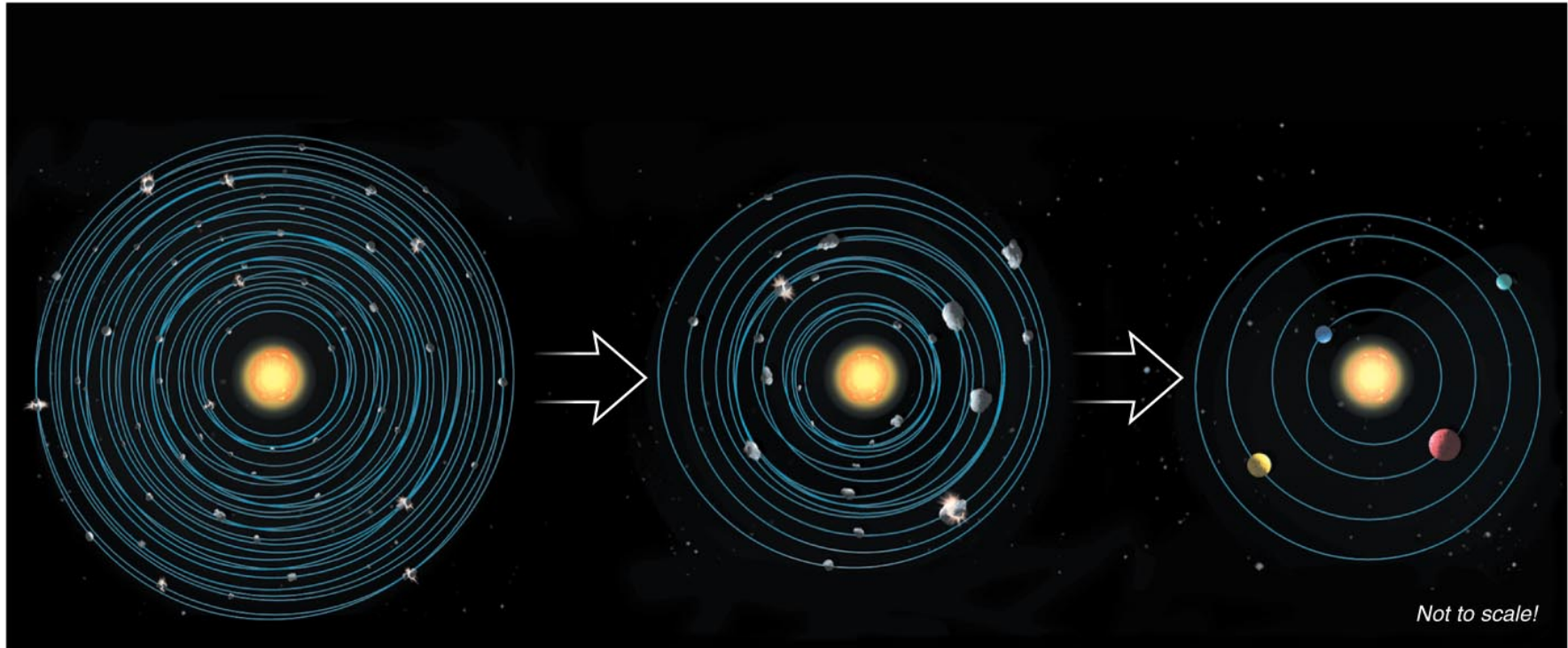


- In nebular theory, young Sun rotated much faster than now.
- Friction between solar magnetic field and solar nebular probably slowed the rotation over time.

Where did asteroids and comets come from?

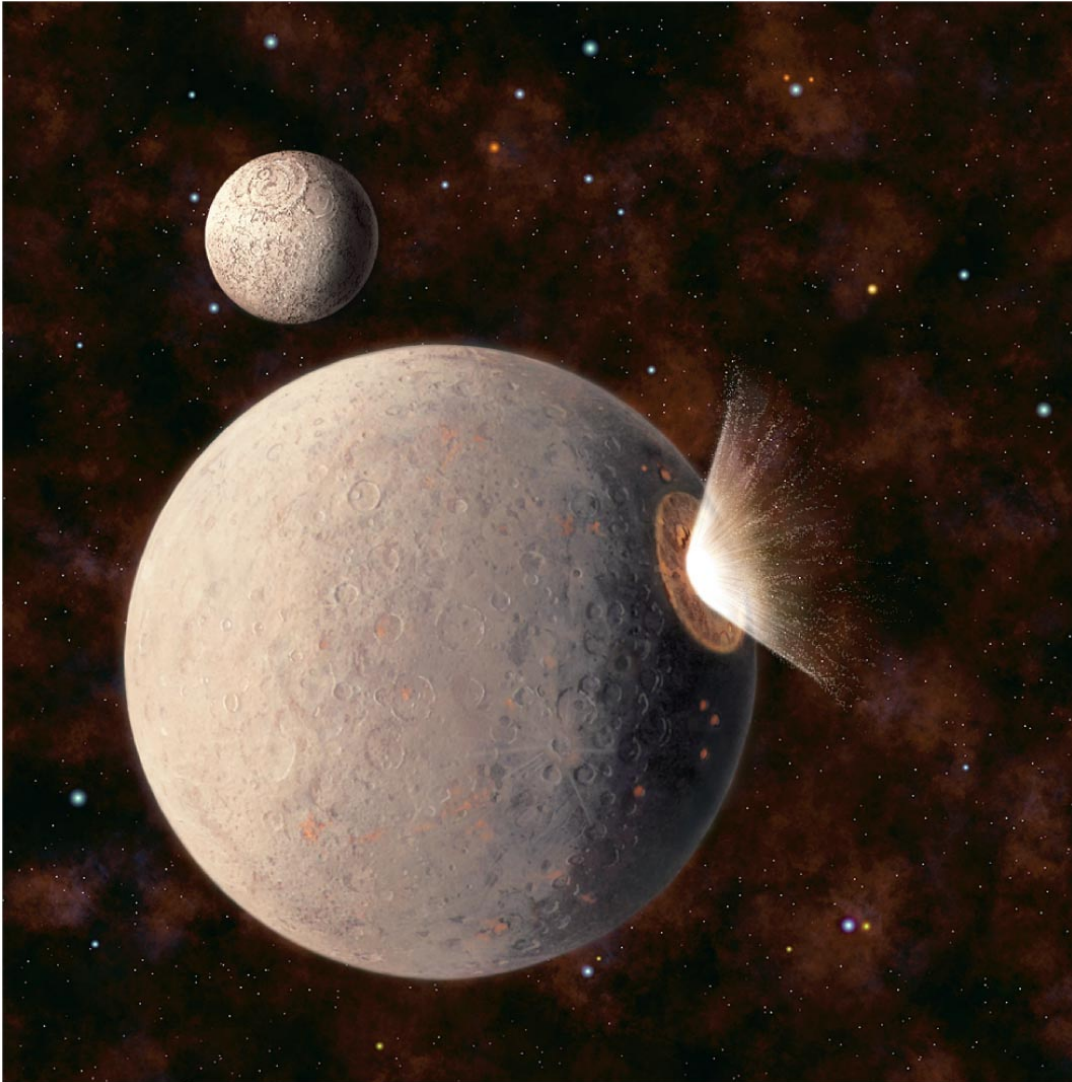


Asteroids and Comets



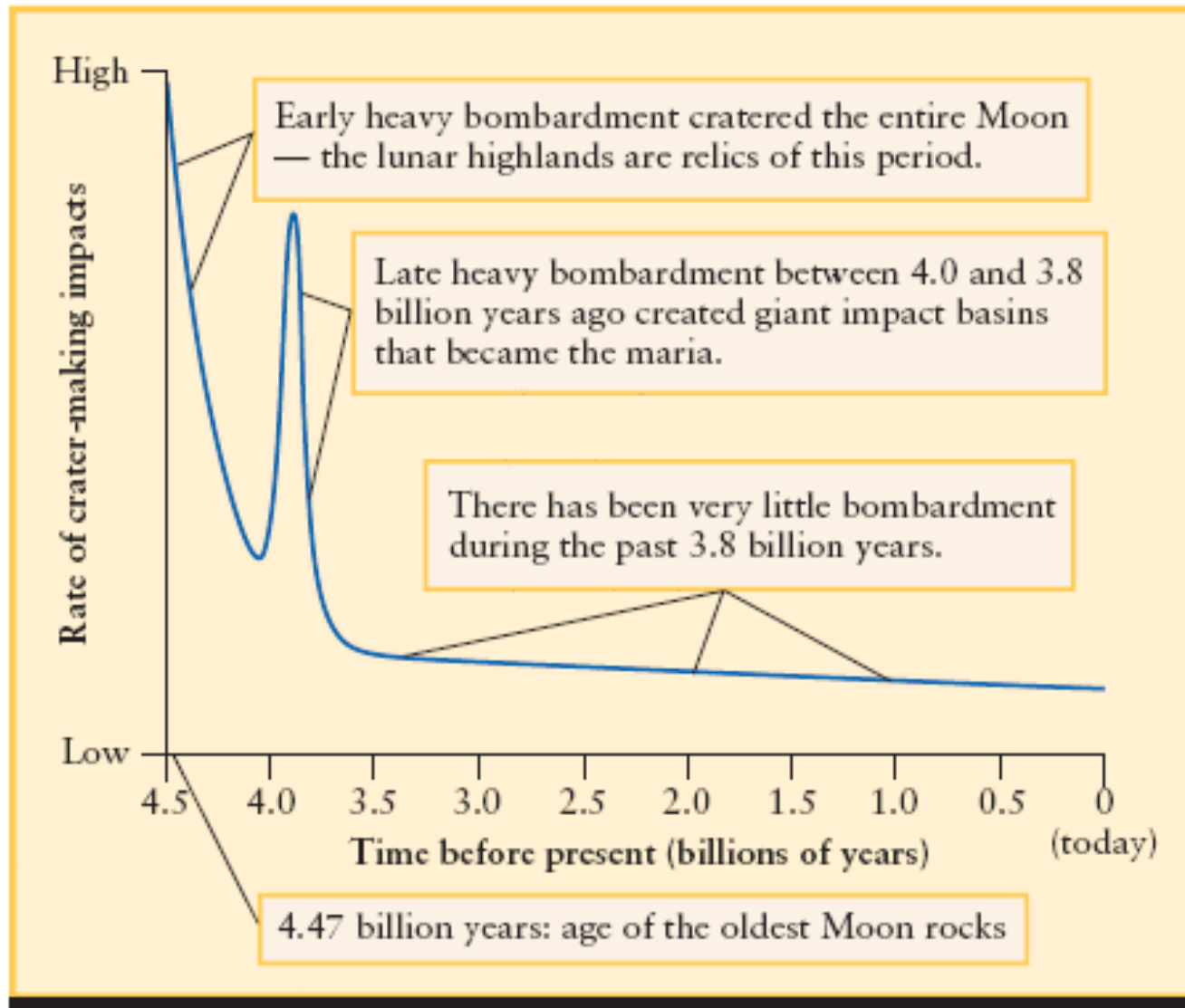
- Leftovers from the accretion process
- Rocky asteroids inside frost line
- Icy comets outside frost line

Heavy Bombardment

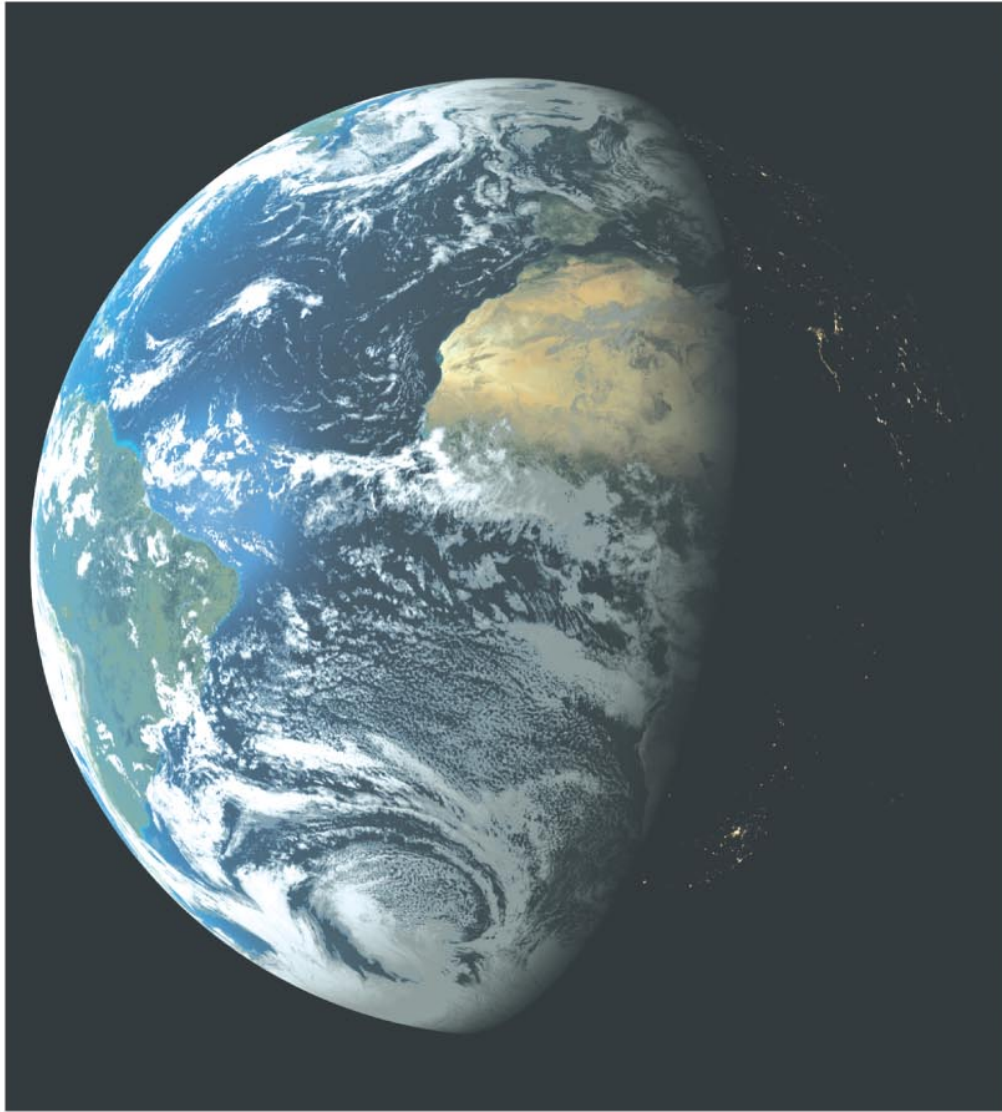


- Leftover planetesimals bombarded other objects in the late stages of solar system formation.

History of Lunar Cratering

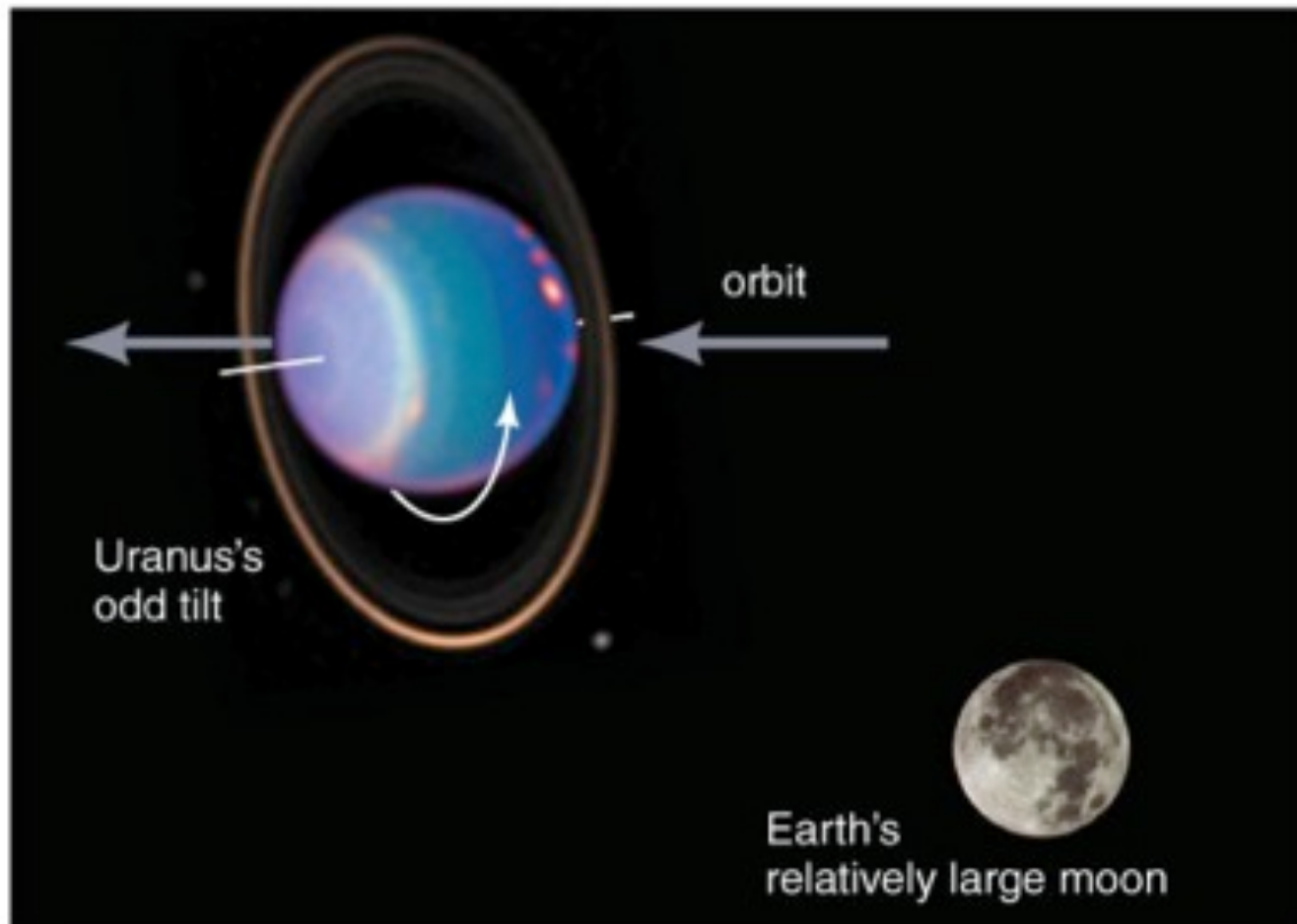


Origin of Earth's Water

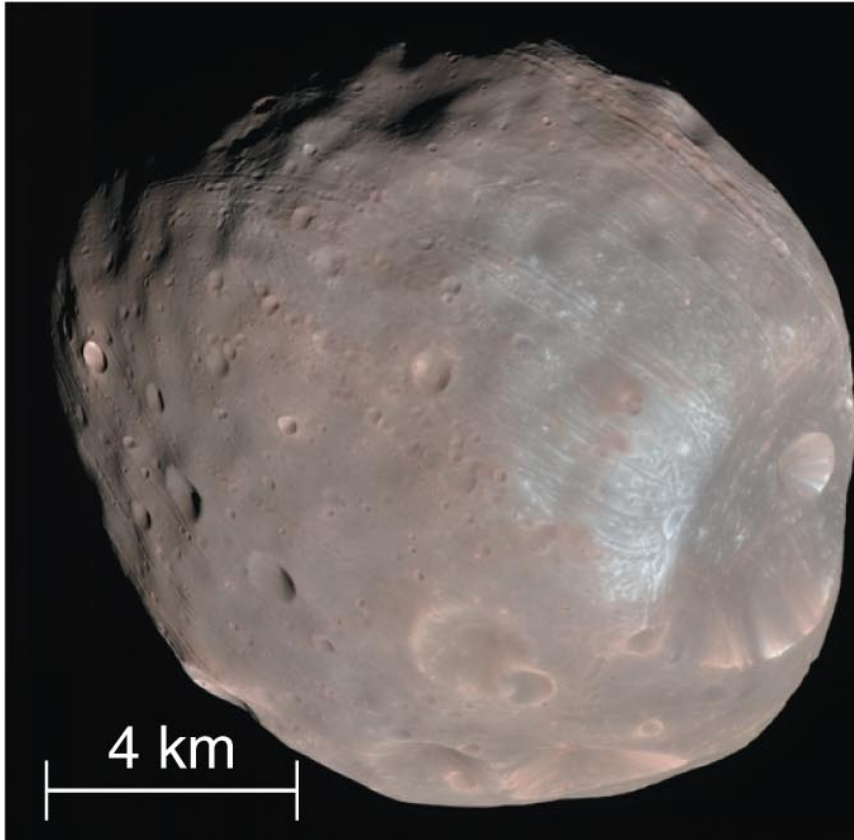


- Water may have come to Earth by way of icy planetesimals.

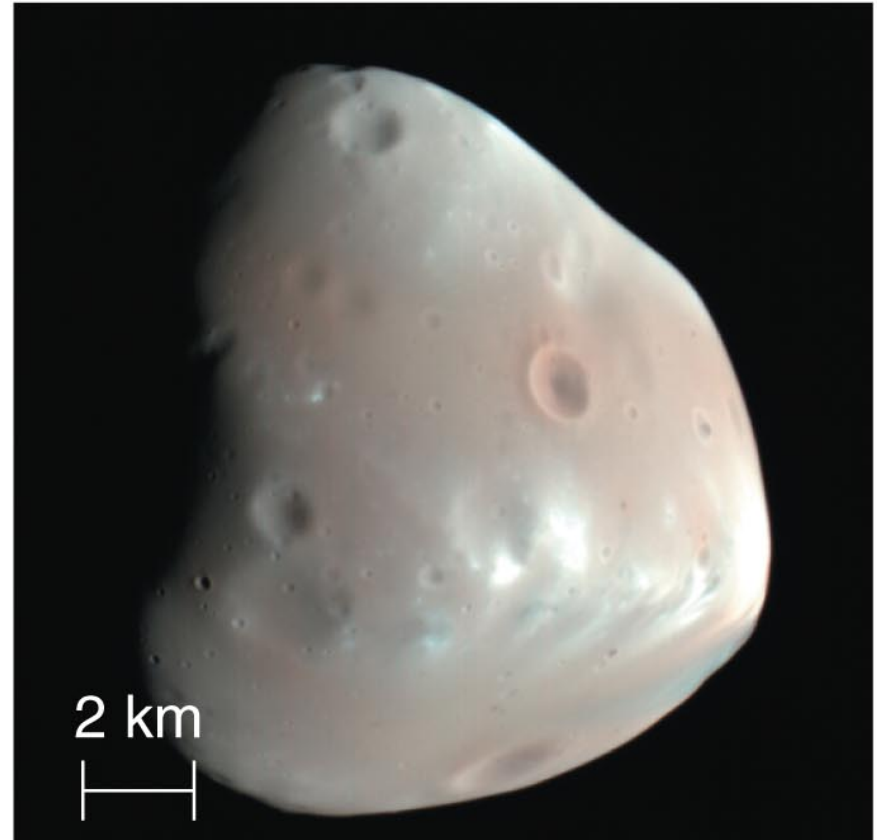
How do we explain "exceptions to the rules"?



Captured Moons



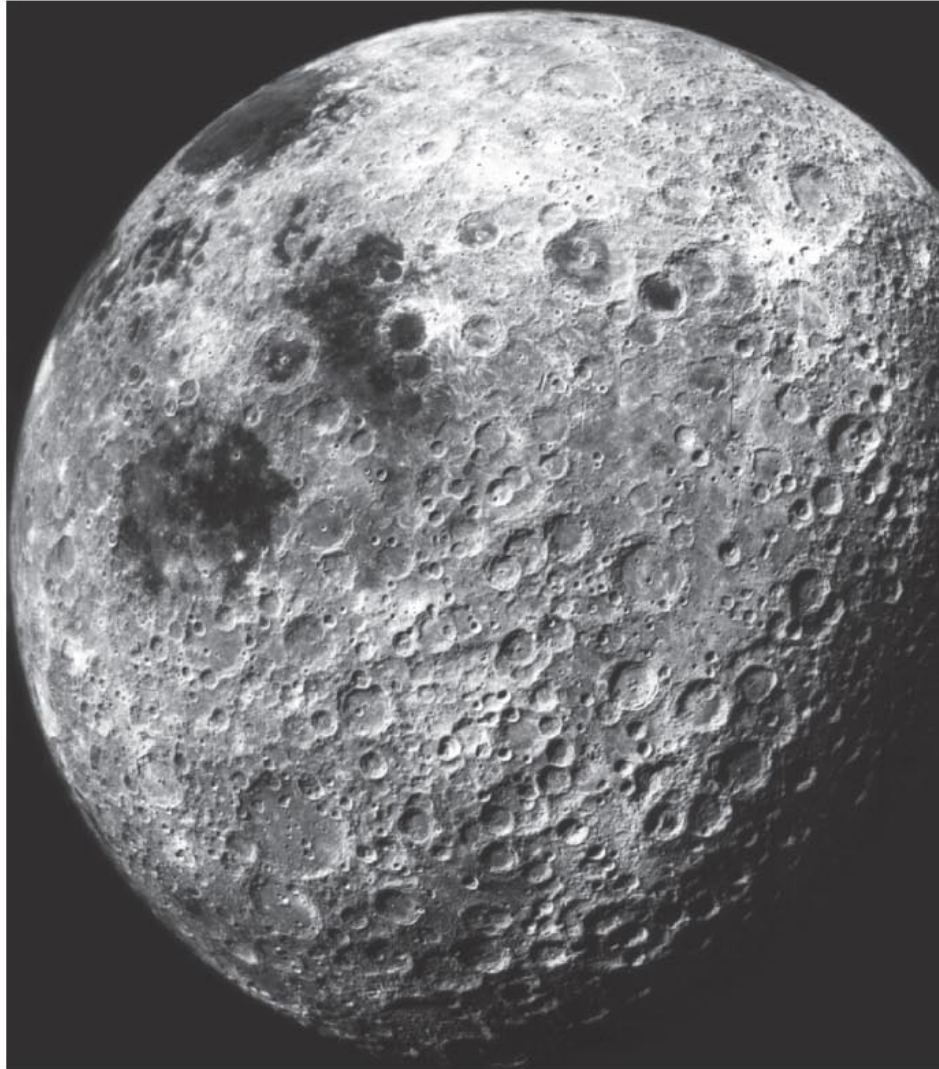
a Phobos



b Deimos

- Unusual moons of some planets may be captured planetesimals.

How do we explain the existence of our Moon?

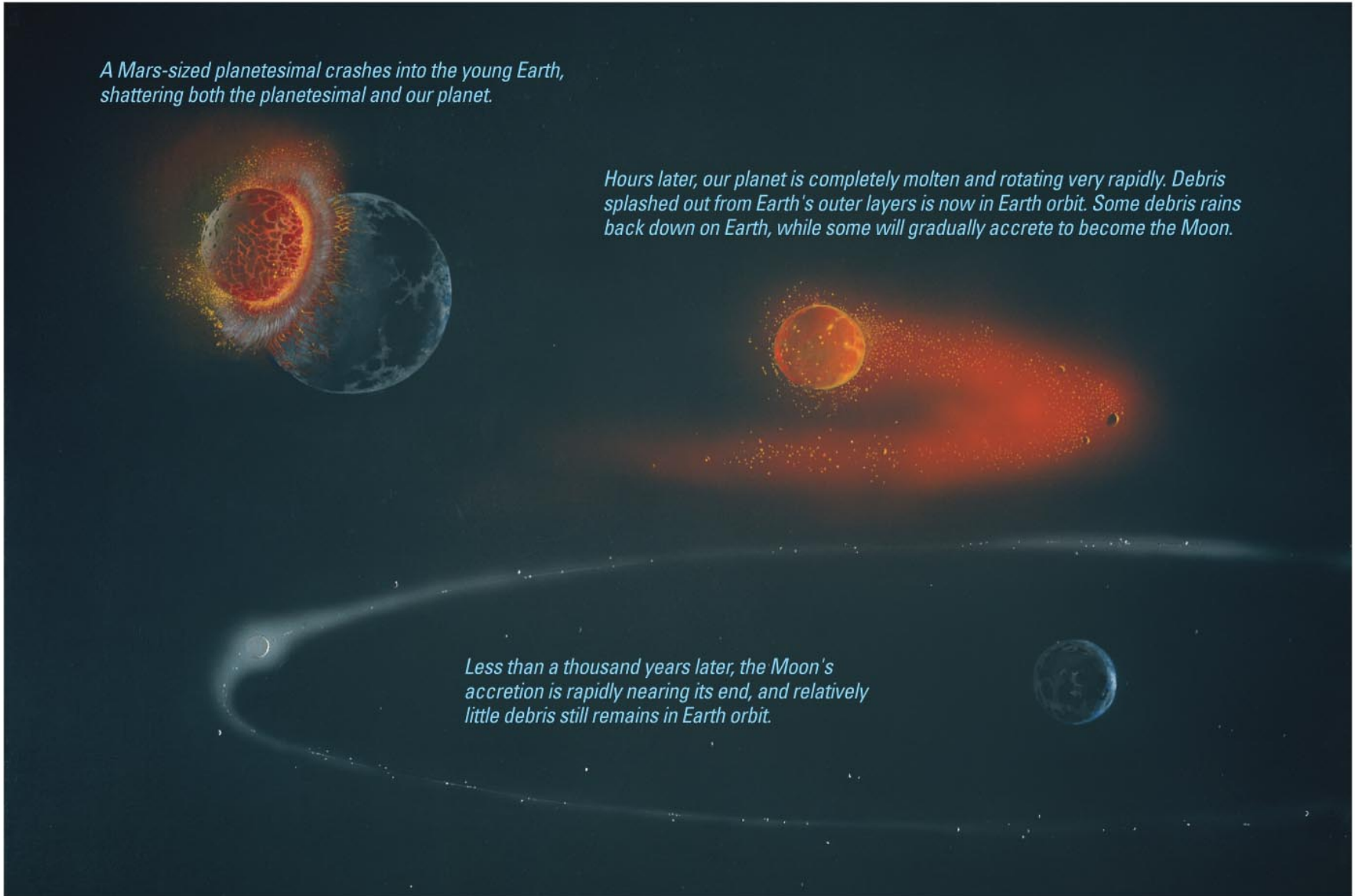


Giant Impact

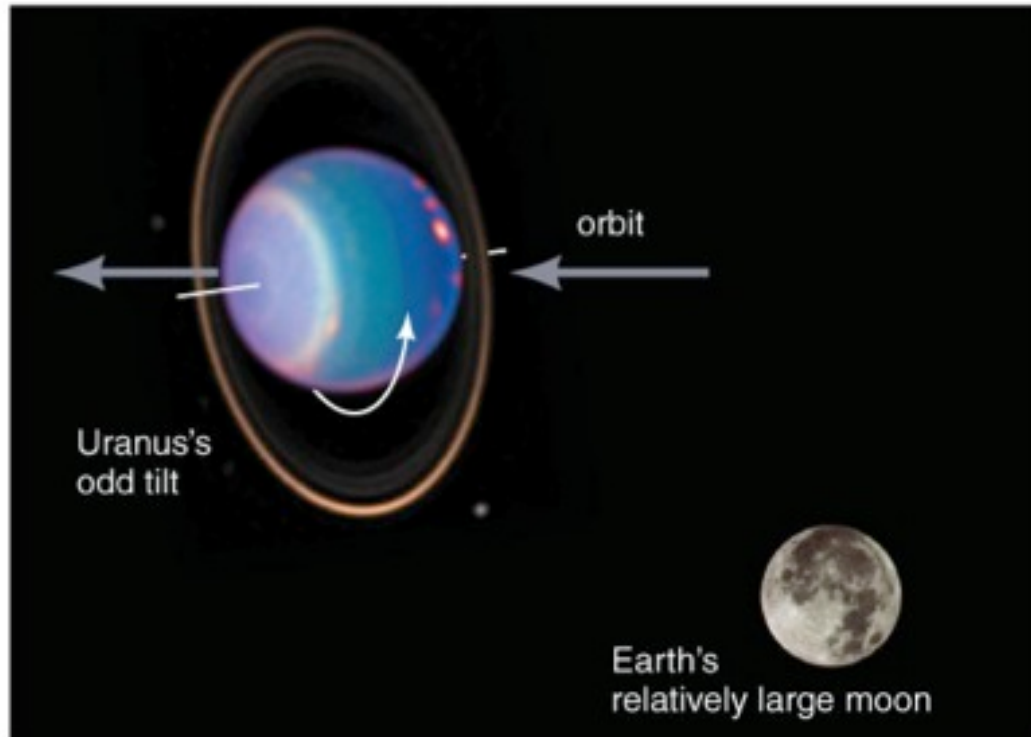
A Mars-sized planetesimal crashes into the young Earth, shattering both the planetesimal and our planet.

Hours later, our planet is completely molten and rotating very rapidly. Debris splashed out from Earth's outer layers is now in Earth orbit. Some debris rains back down on Earth, while some will gradually accrete to become the Moon.

Less than a thousand years later, the Moon's accretion is rapidly nearing its end, and relatively little debris still remains in Earth orbit.



Odd Rotation



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

Thought Question

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

- a) Jovian planets would have formed closer to Sun.
- b) There would be no asteroids.
- c) There would be no comets.
- d) Terrestrial planets would be larger.

Thought Question

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

- a) **Jovian planets would have formed closer to Sun.**
- b) There would be no asteroids.
- c) There would be no comets.
- d) Terrestrial planets would be larger.

What have we learned?

- **What caused the orderly patterns of motion in our solar system?**
 - 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.
- **Why are there two major types of planets?**
 - Only rock and metals condensed inside the frost line.
 - Rock, metals, and ices condensed outside the frost line.
 - Larger planetesimals outside the frost line drew in H and He gas.

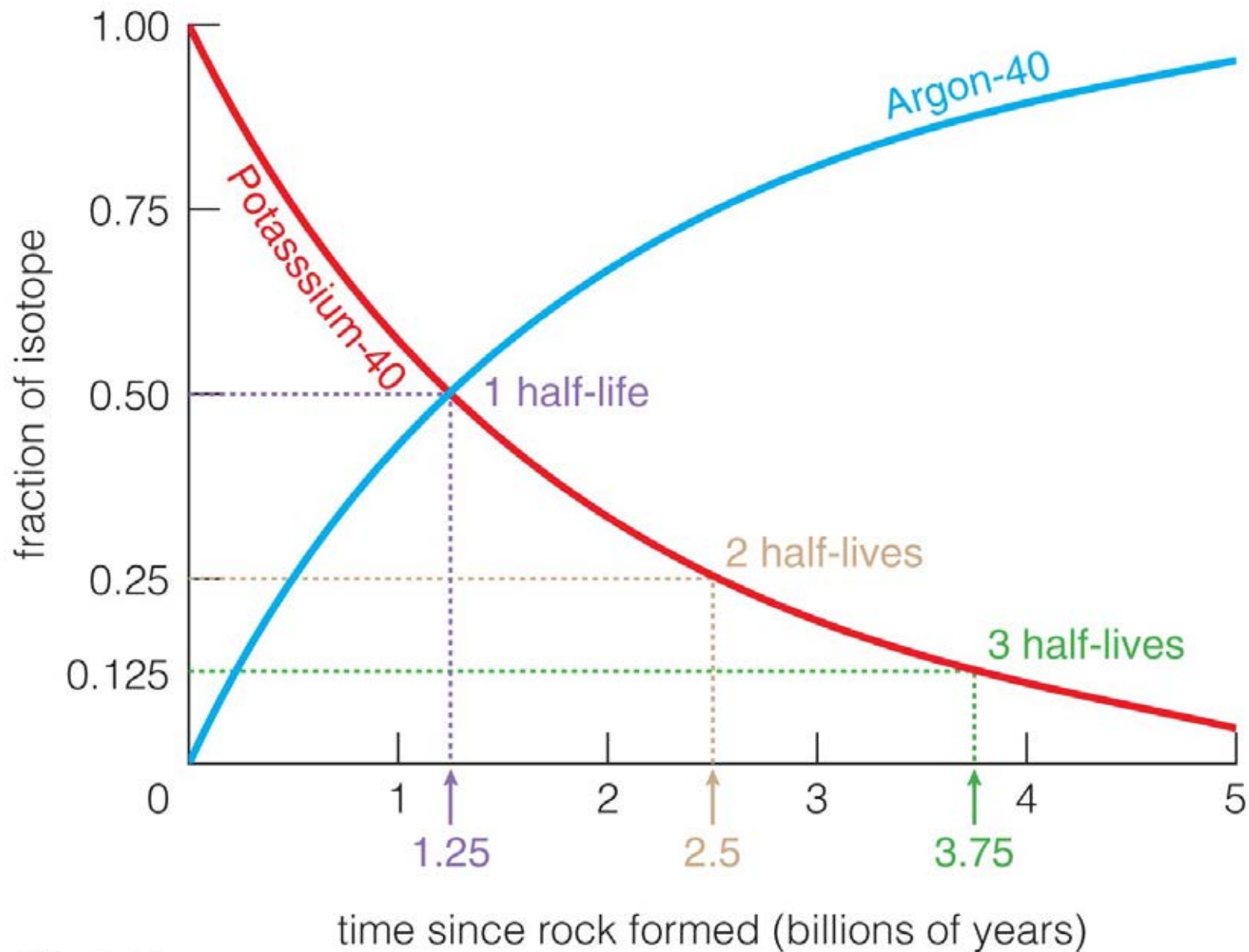
What have we learned?

- **Where did asteroids and comets come from?**
 - They are leftover planetesimals, according to the nebular theory.
- **How do we explain "exceptions to the rules"?**
 - Bombardment of newly formed planets by planetesimals may explain the exceptions.

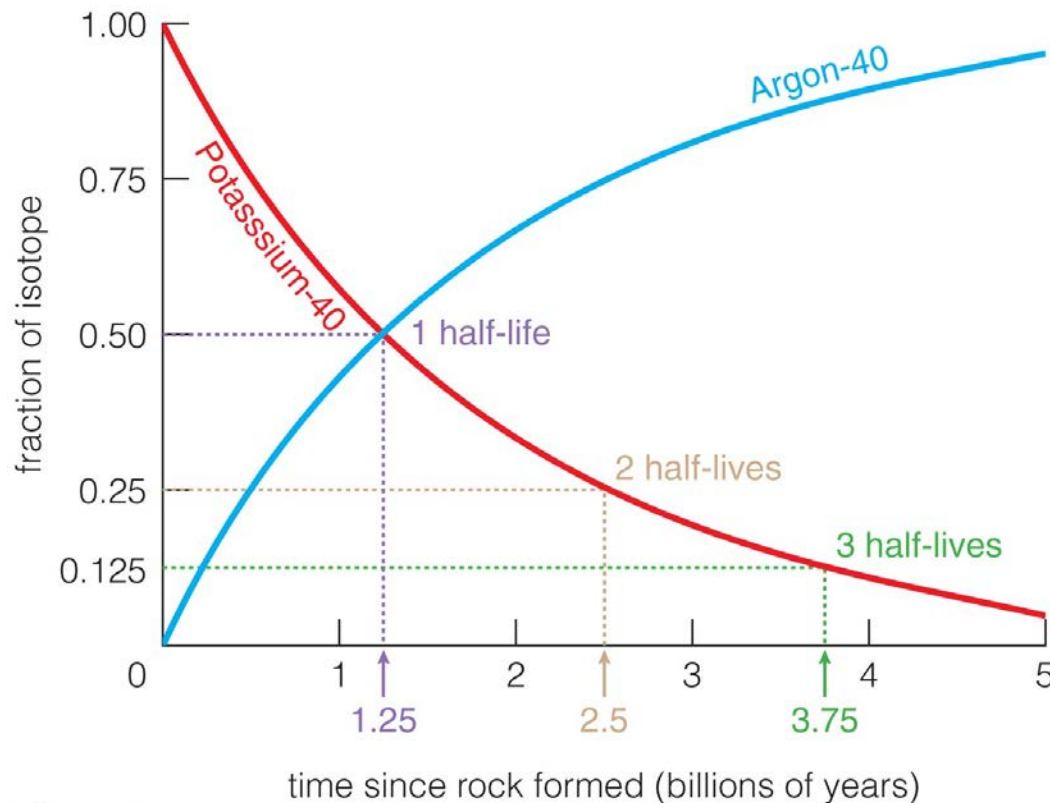
8.3 The Age of the Solar System

- Our goals for learning:
 - **How do we measure the age of a rock?**
 - **How do we know the age of the solar system?**

How do we measure the age of a rock ?



Radioactive Decay



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

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

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**

How do we know the age of the solar system?

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

What have we learned?

- **How do we measure the age of a rock?**
 - Some isotopes decay with a well-known half-life.
 - Comparing the proportions of those isotopes with their decay products tells us age of rock.
- **How do we know the age of the solar system?**
 - Radiometric dating indicates that planets formed 4.5 billion years ago.