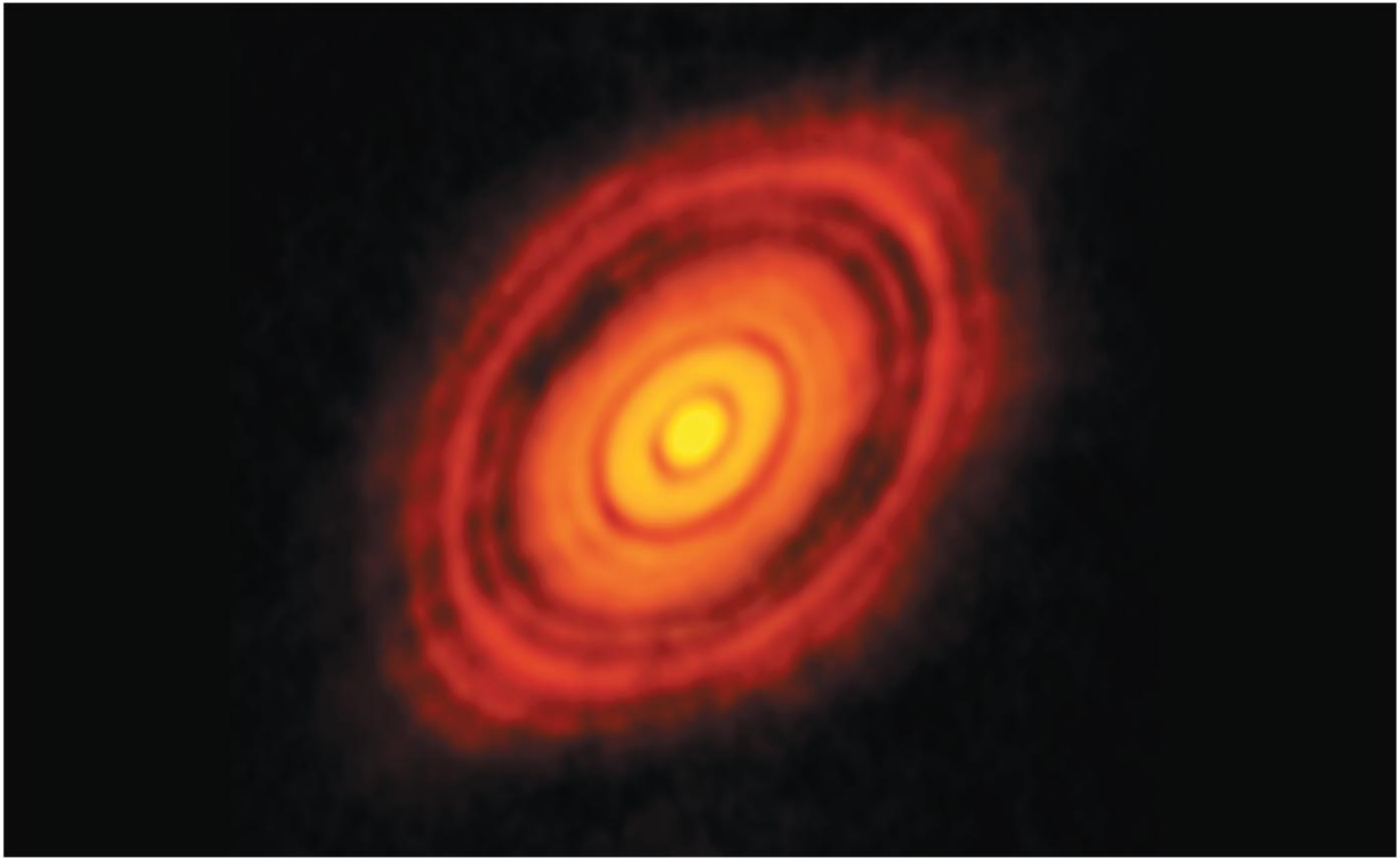
# Chapter 8: Formation of the Solar System

# Formation of the Solar System



# 8.1 The Search for Origins

- Our goals for learning:
  - **How did we arrive at a theory of solar system formation?**
  - **Where did the solar system come from?**

# How did we arrive at a theory of solar system formation?

- Four major features needed to be explained
- Several reasonable hypotheses were explored, the most important of which are the following:
  - Nebular hypothesis
  - Close encounter hypothesis

# What properties of our solar system must a formation theory explain?

1. Patterns of motion of the large bodies
   - Orbit in same direction and plane
2. Existence of two types of planets
   - Terrestrial and jovian
3. Existence of smaller bodies
   - Asteroids and comets
4. Notable exceptions to usual patterns
   - Rotation of Uranus, Earth's Moon, etc.

# Nebular Theory

- The *nebular theory* states that our solar system formed from the gravitational collapse of a giant interstellar gas cloud—the *solar nebula*.
  - (*Nebula* is the Latin word for cloud.)
- Kant and Laplace proposed the *nebular hypothesis* over two centuries ago.
- A large amount of evidence now supports this idea.

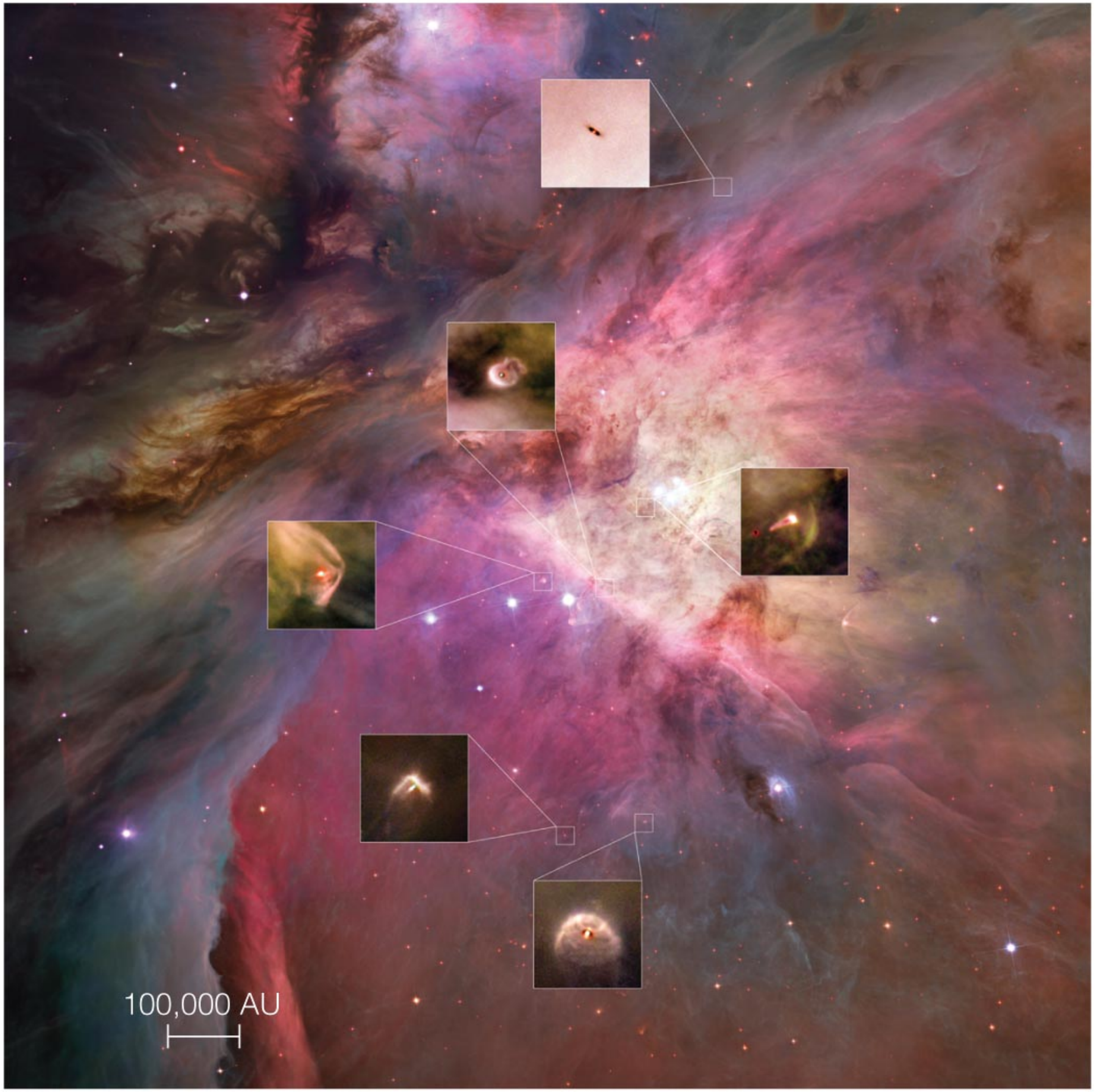
Immanuel Kant (1724 – 1804)

Pierre-Simon Laplace (1749 – 1827)

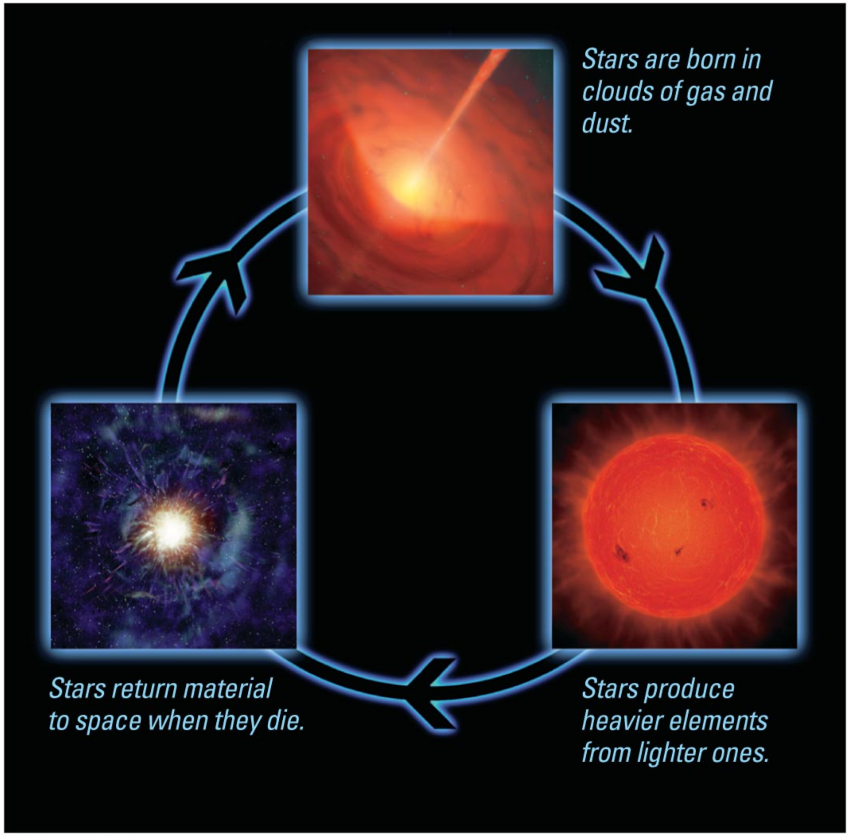
# Close Encounter Hypothesis

- 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?



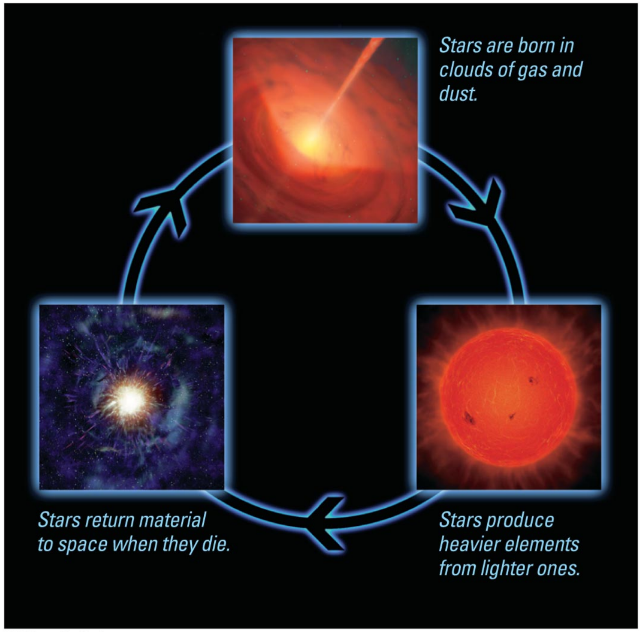
# Galactic Recycling




- 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.





Young star cluster – Carina constellation


Old globular star cluster – M31

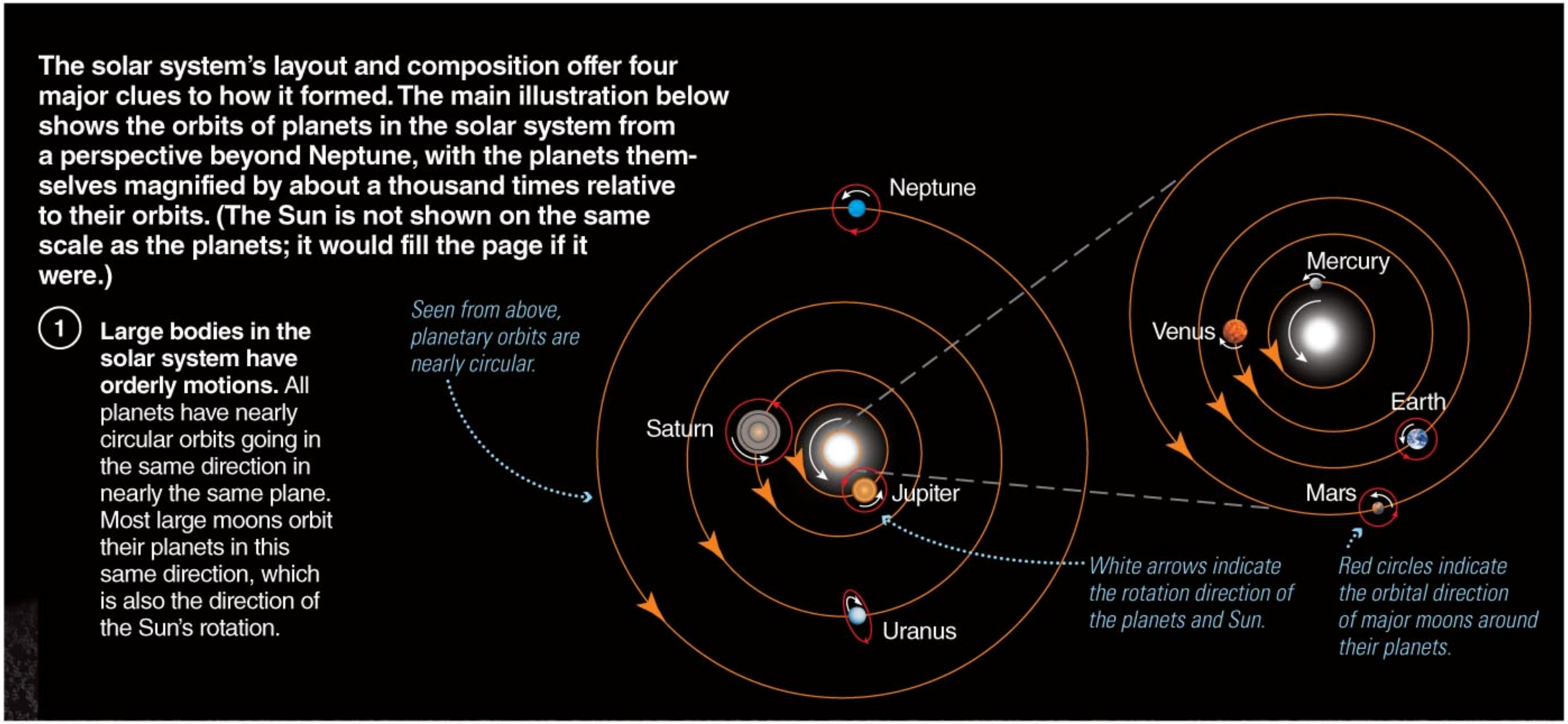
# What have we learned?

- **How did we arrive at a theory of solar system formation?**
  - Hypotheses arose to explain four 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.

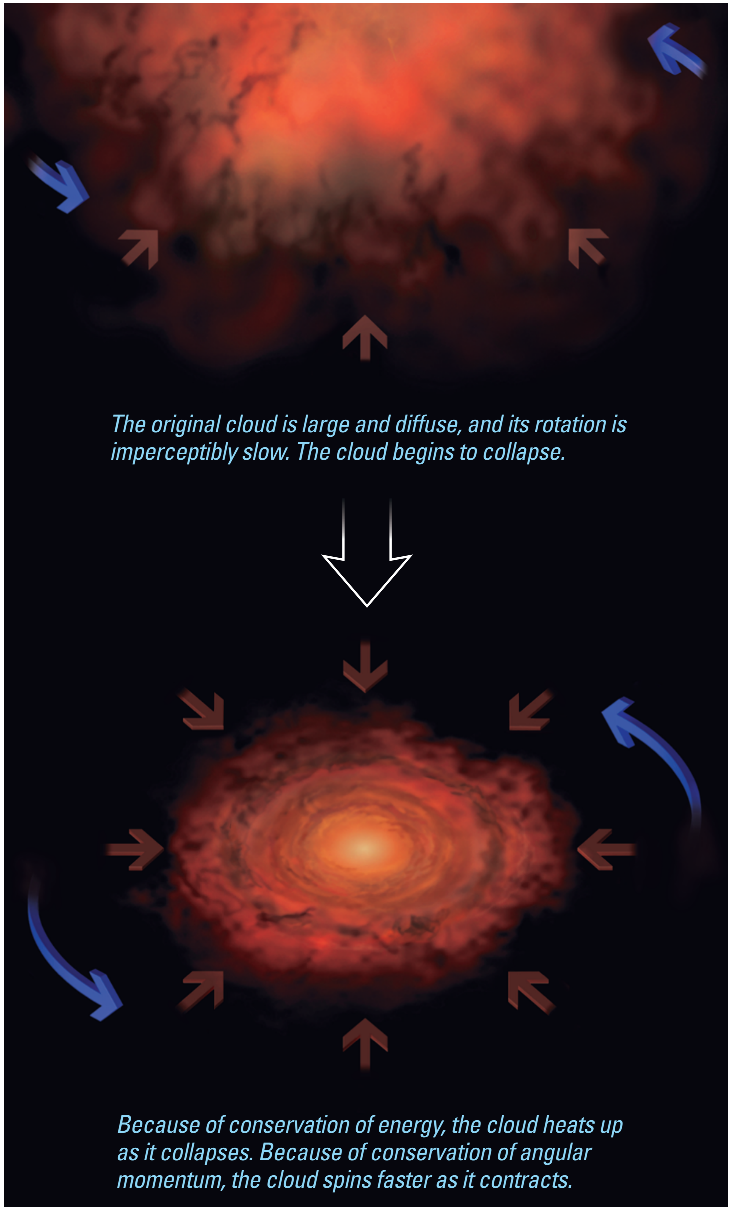
# 8.2 Explaining the Major Features of the Solar System

- 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?

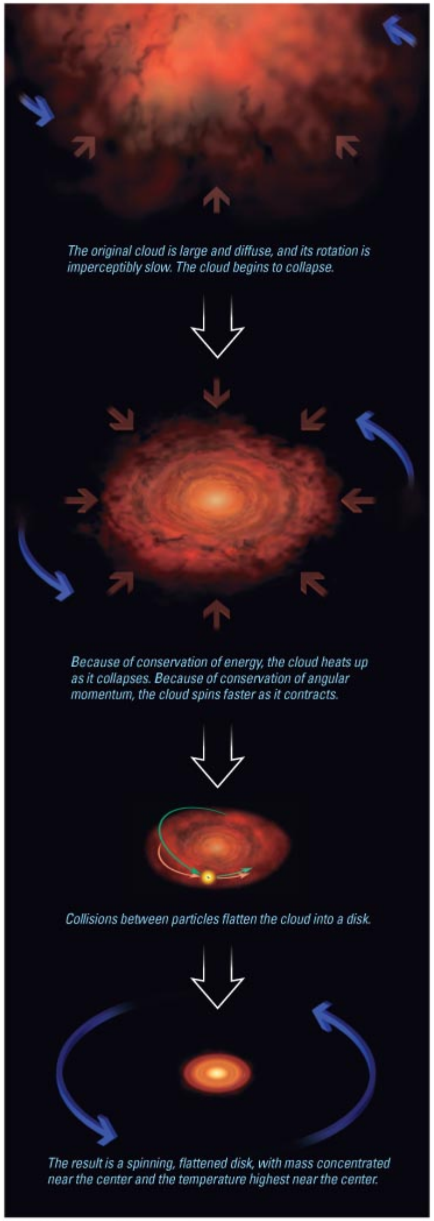


# Conservation of Angular Momentum




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

# Flattening




- Collisions between particles in the cloud caused it to flatten into a disk.
- At the same time, flattening corresponds to a faster spinning, due to the conservation of angular momentum

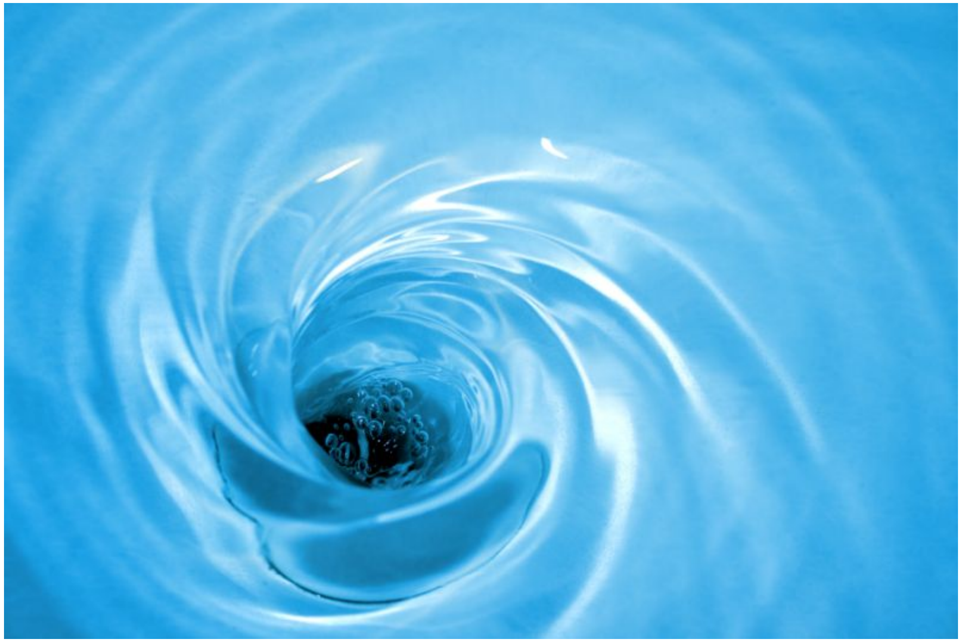
# Flattening

- Collisions between gas particles in cloud gradually reduce random motions.
- Collisions between gas particles also reduce up and down motions.
- Spinning cloud flattens as it shrinks.

What does this remind you of?

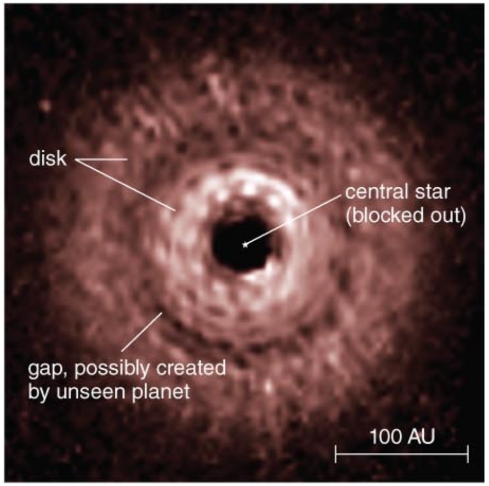
# Flattening

- Collisions between gas particles in cloud gradually reduce random motions.
- Collisions between gas particles also reduce up and down motions.
- Spinning cloud flattens as it shrinks.

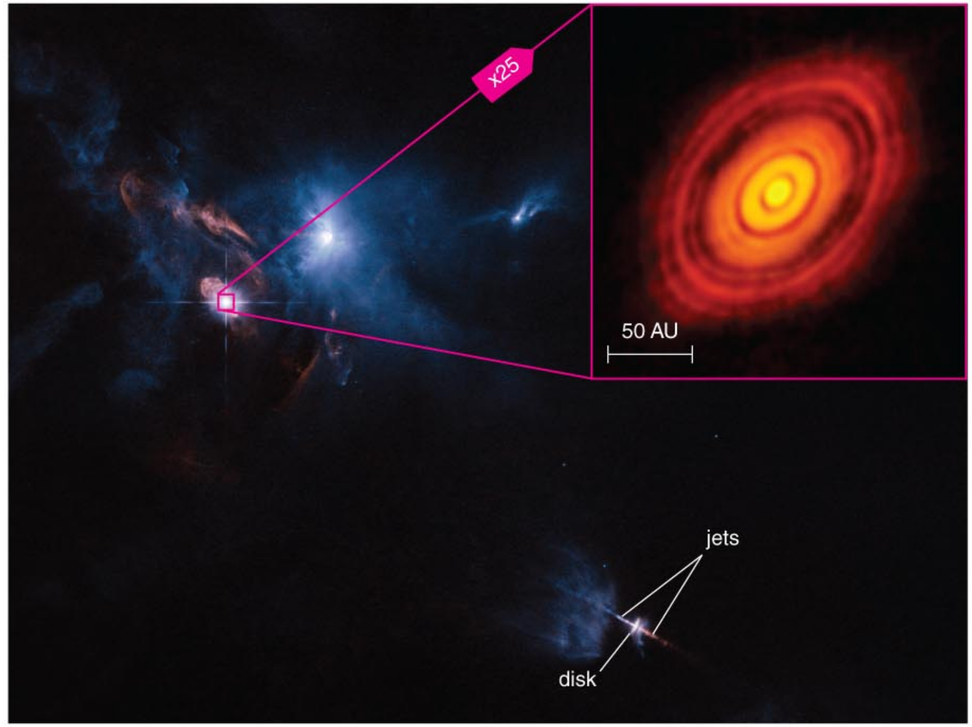


However, in case of the solar system not all material goes down the ‘drain’ (the Sun)

# Disks around Other Stars



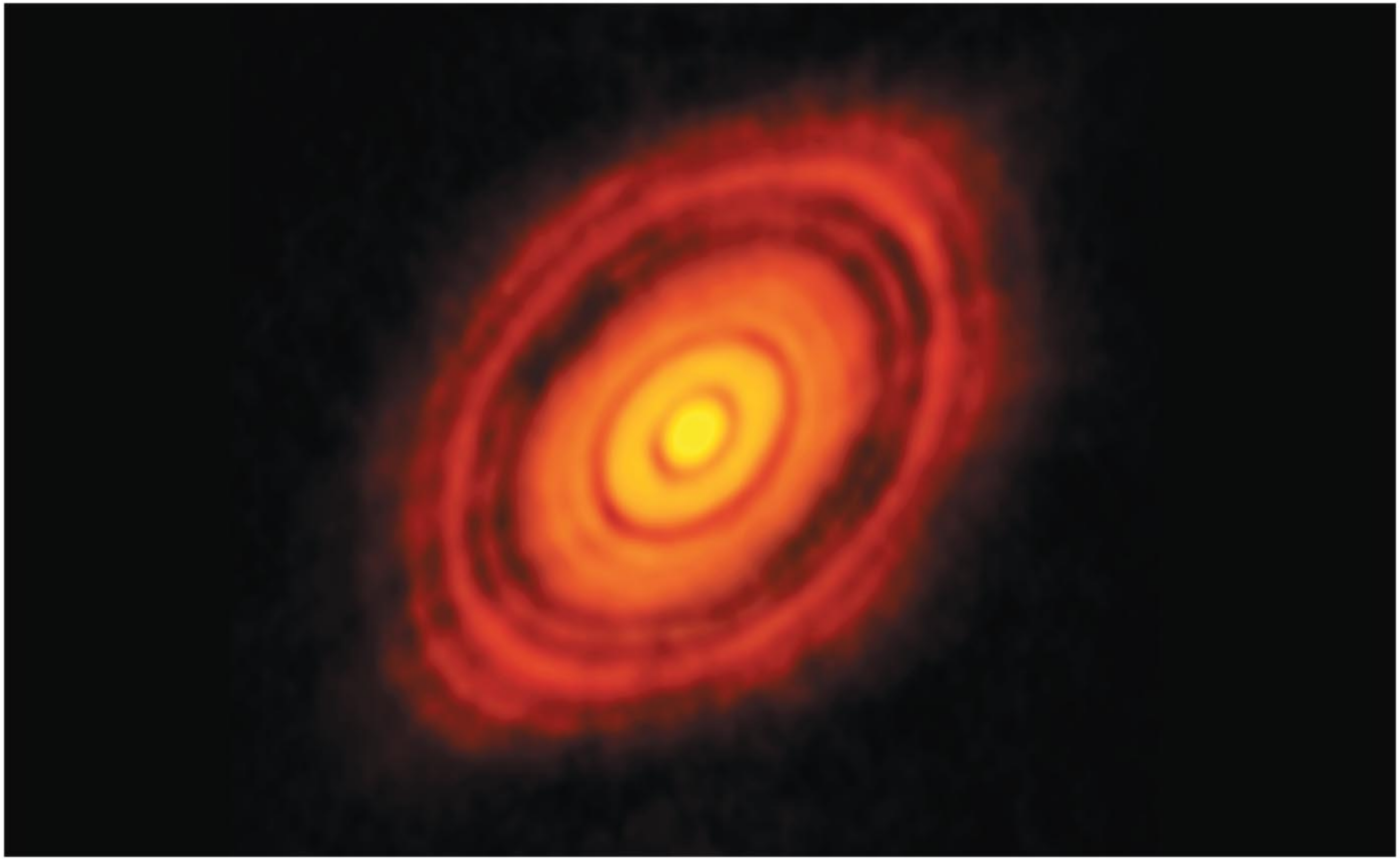

**a** This Hubble Space Telescope image shows a flattened, spinning disk around the star TW Hydrae. This particular disk also shows at least one circular "gap" in which material seems to have been cleared away, probably by a planet forming in the disk, which would have a gravitational attraction that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

# Disks around Other Stars



- The gaps in this protoplanetary disk, as imaged by ALMA, are likely due to forming planets.

# Why are there two major types of planets?

**2** **Planets fall into two major categories:** Small, rocky terrestrial planets and large, hydrogen-rich jovian planets.

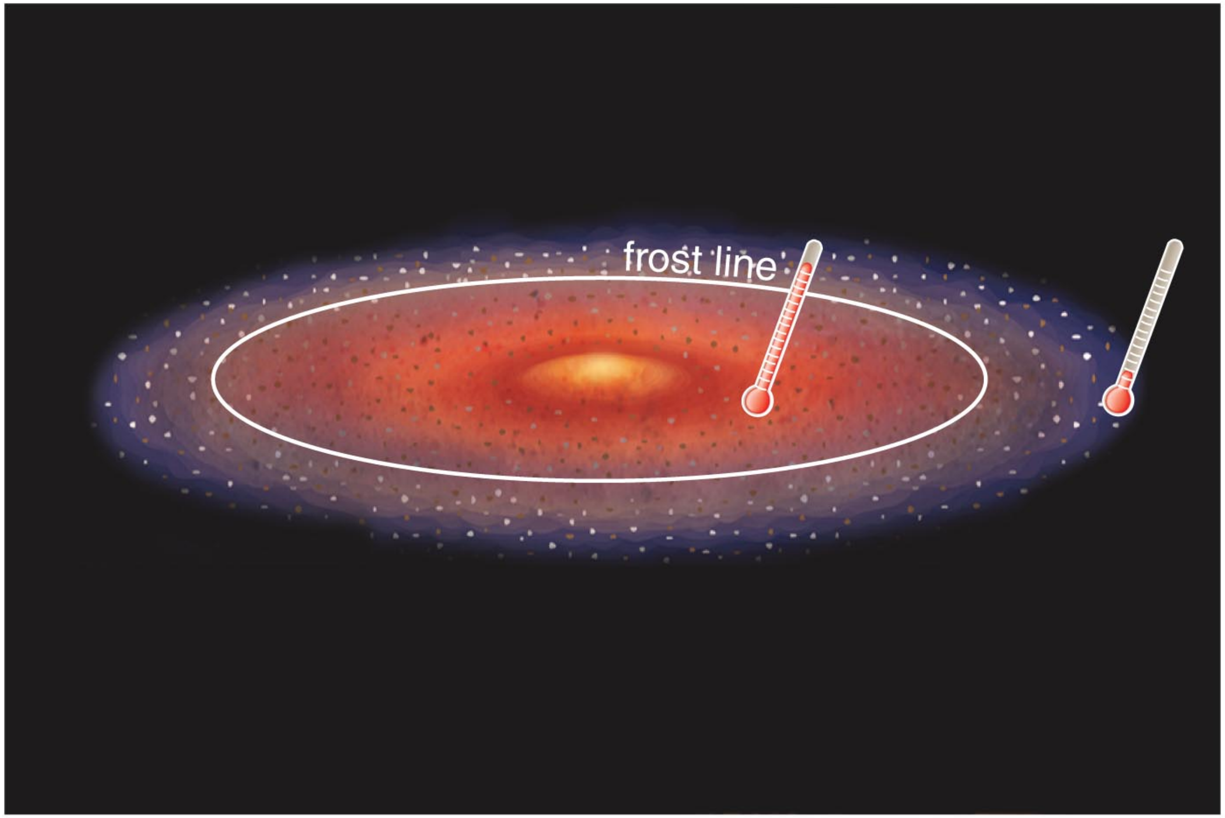

***Terrestrial Planets:***

- *small in mass and size*
- *close to the Sun*
- *made of metal and rock*
- *few moons and no rings*

***Jovian Planets:***

- *large mass and size*
- *far from the Sun*
- *made of H, He, and hydrogen compounds*
- *rings and many moons*

# Frost line: within and beyond

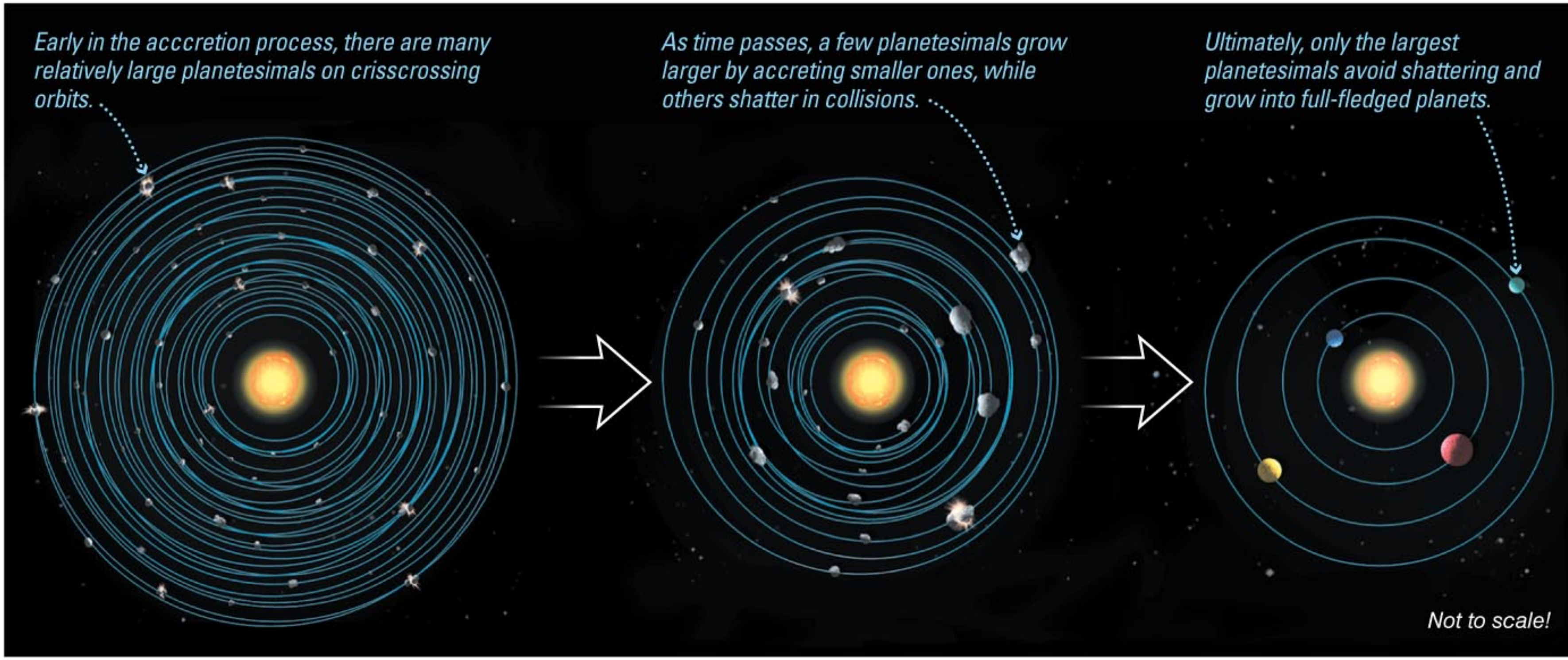



- Inside the ***frost line***: too hot for hydrogen compounds to form ices
- Outside the ***frost line***: cold enough for ices to form

# How did the terrestrial planets form?

- 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.
  - This process is called *accretion*.

# Accretion of Planetesimals

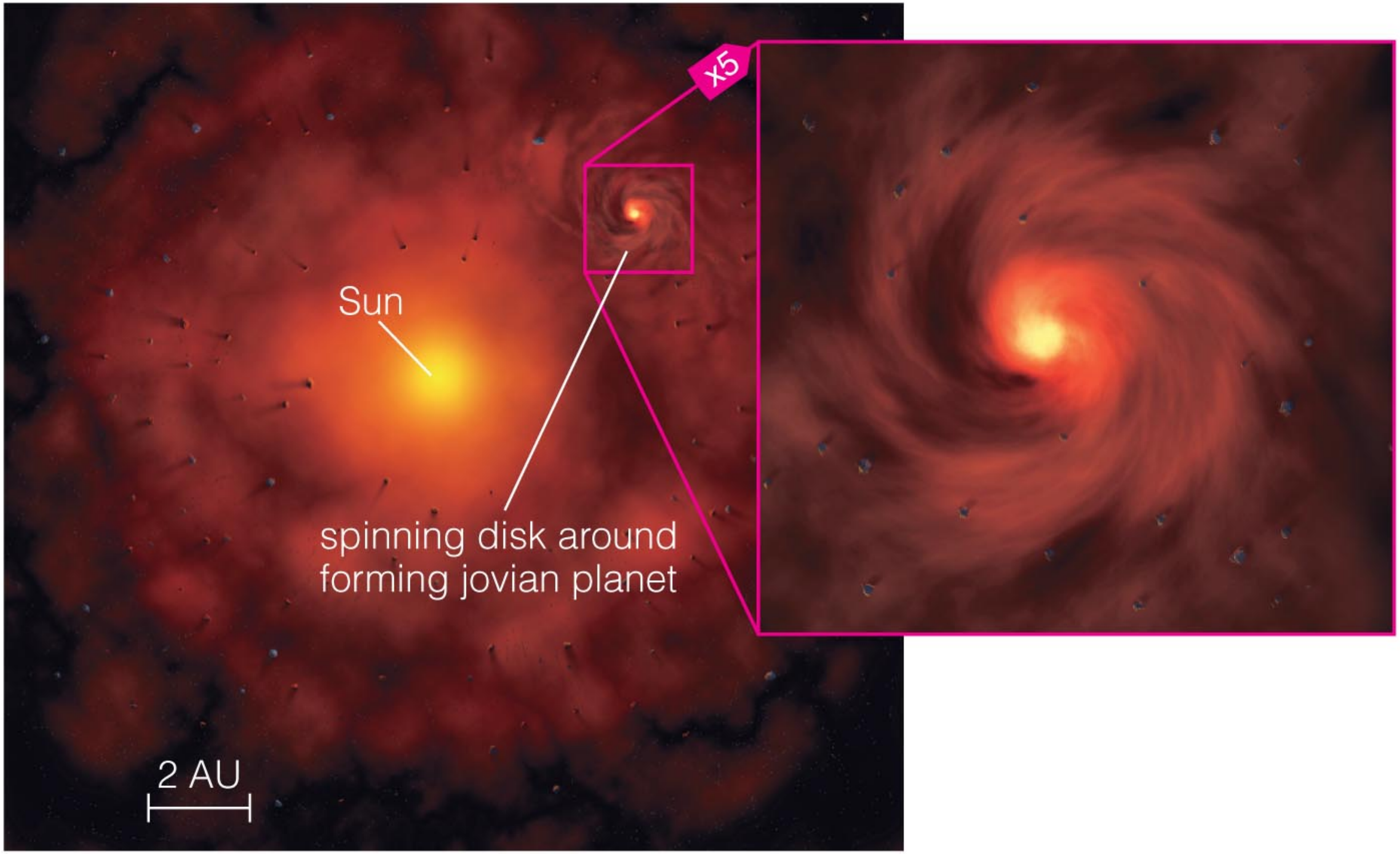



- Many smaller objects collected into just a few large ones.

# 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?

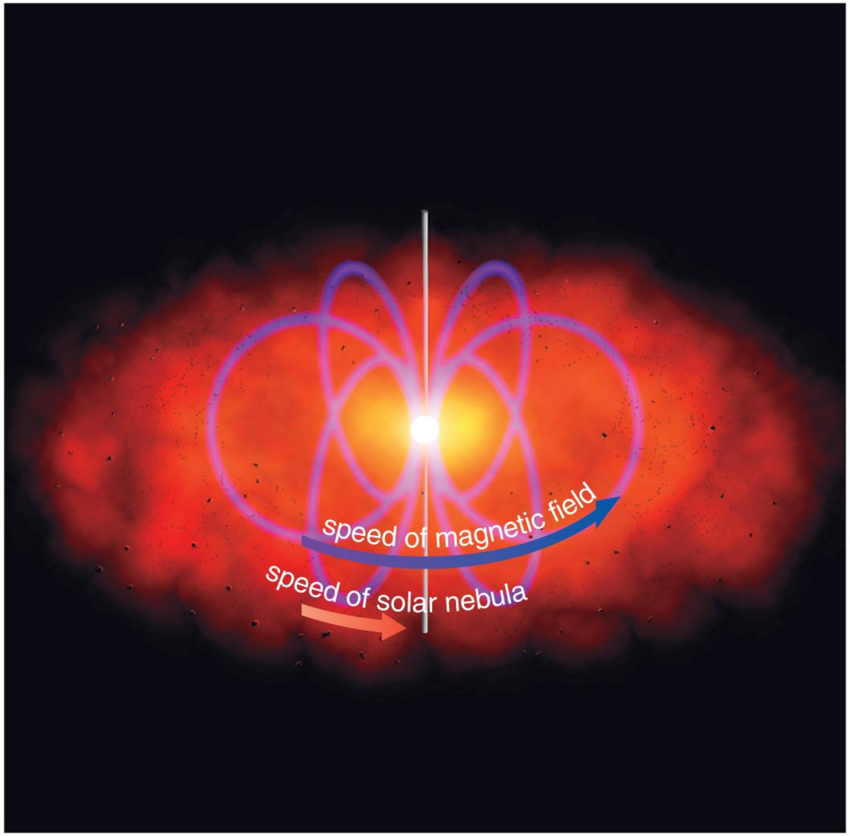



- Moons of jovian planets form in miniature disks.

# How did the jovian planets form?

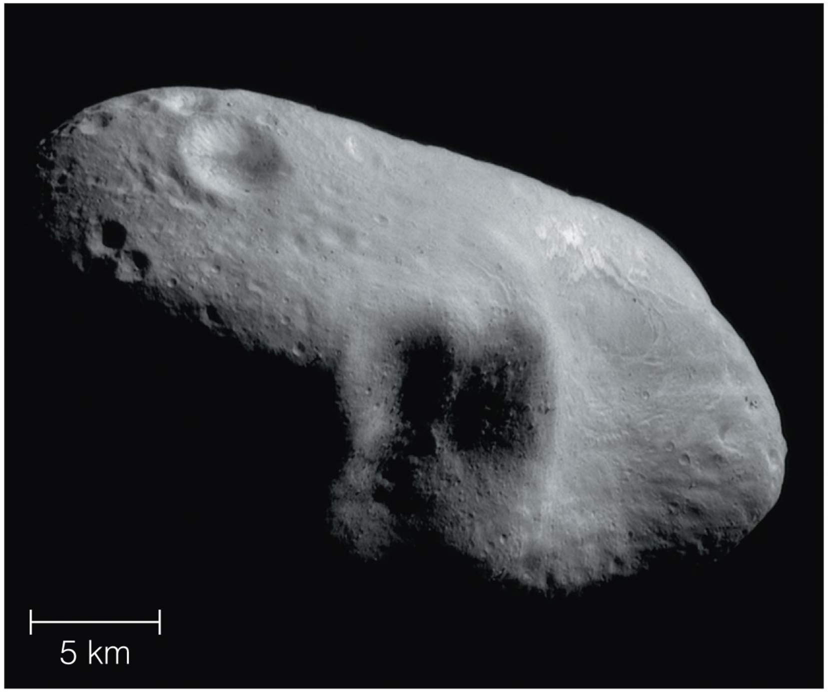
- A combination of photons and the ***solar wind***—outflowing matter from the Sun—blew away the leftover gases.

# Solar Rotation

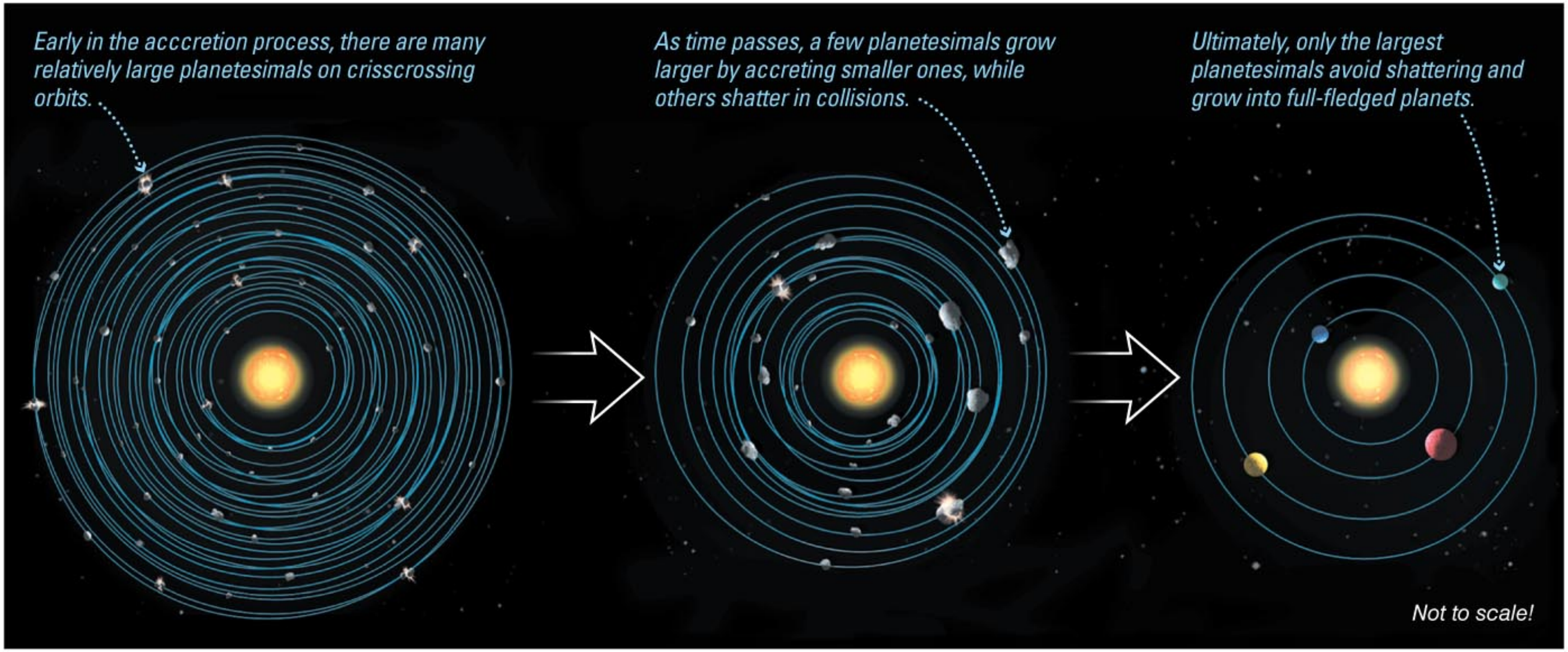



- In nebular theory, young Sun rotated much faster than now.
- Friction between solar magnetic field and solar nebular probably slowed the rotation over time.

# Where did asteroids and comets come from?

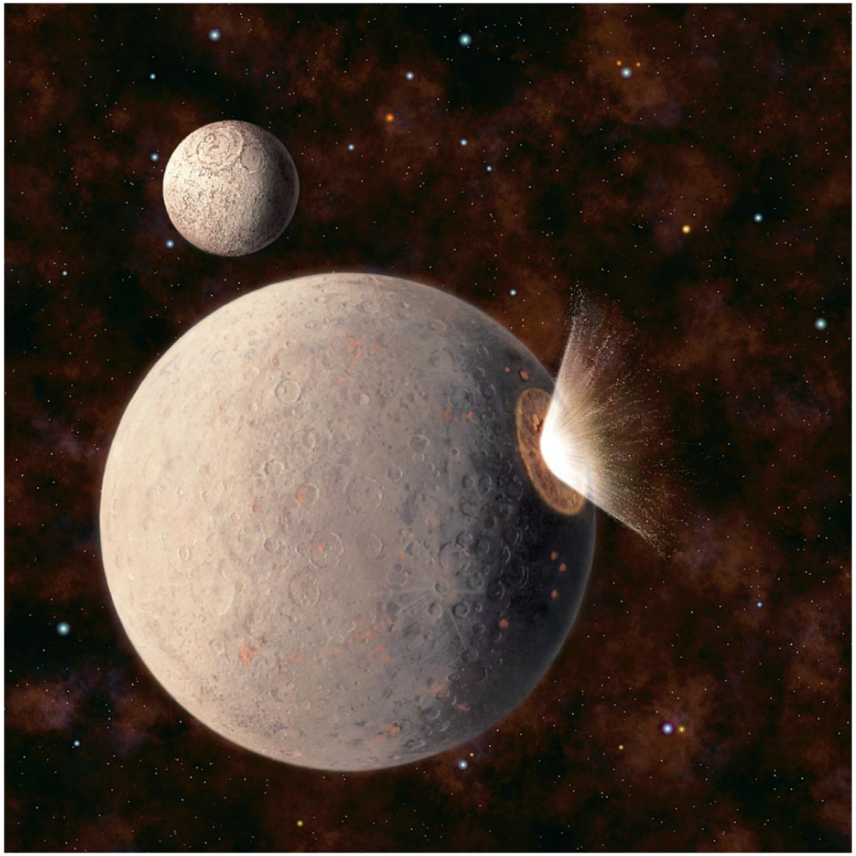



# Asteroids and Comets



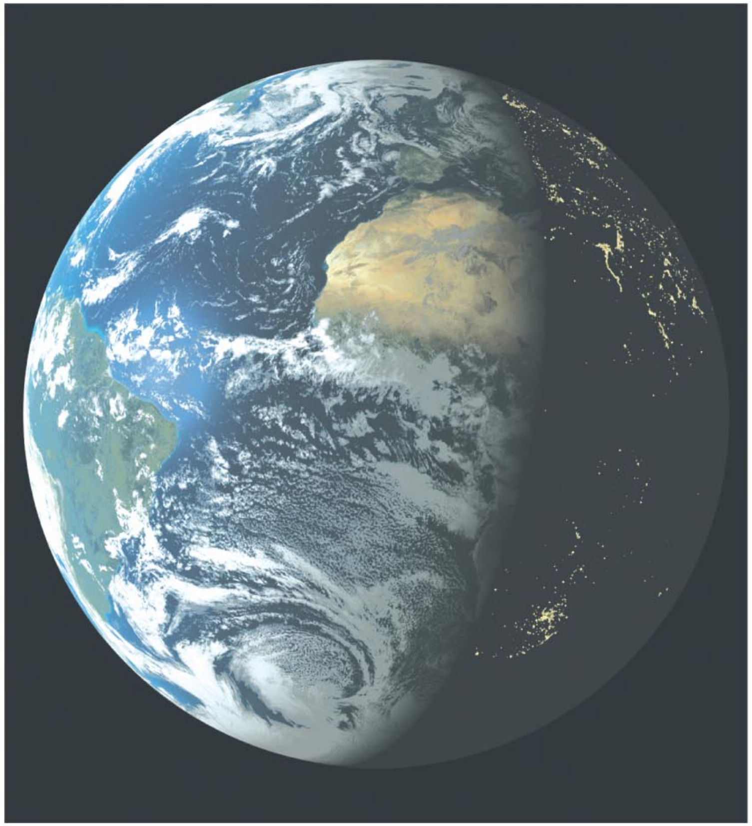

- Leftovers from the accretion process
- Rocky asteroids inside frost line
- Icy comets outside frost line

# Heavy Bombardment



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

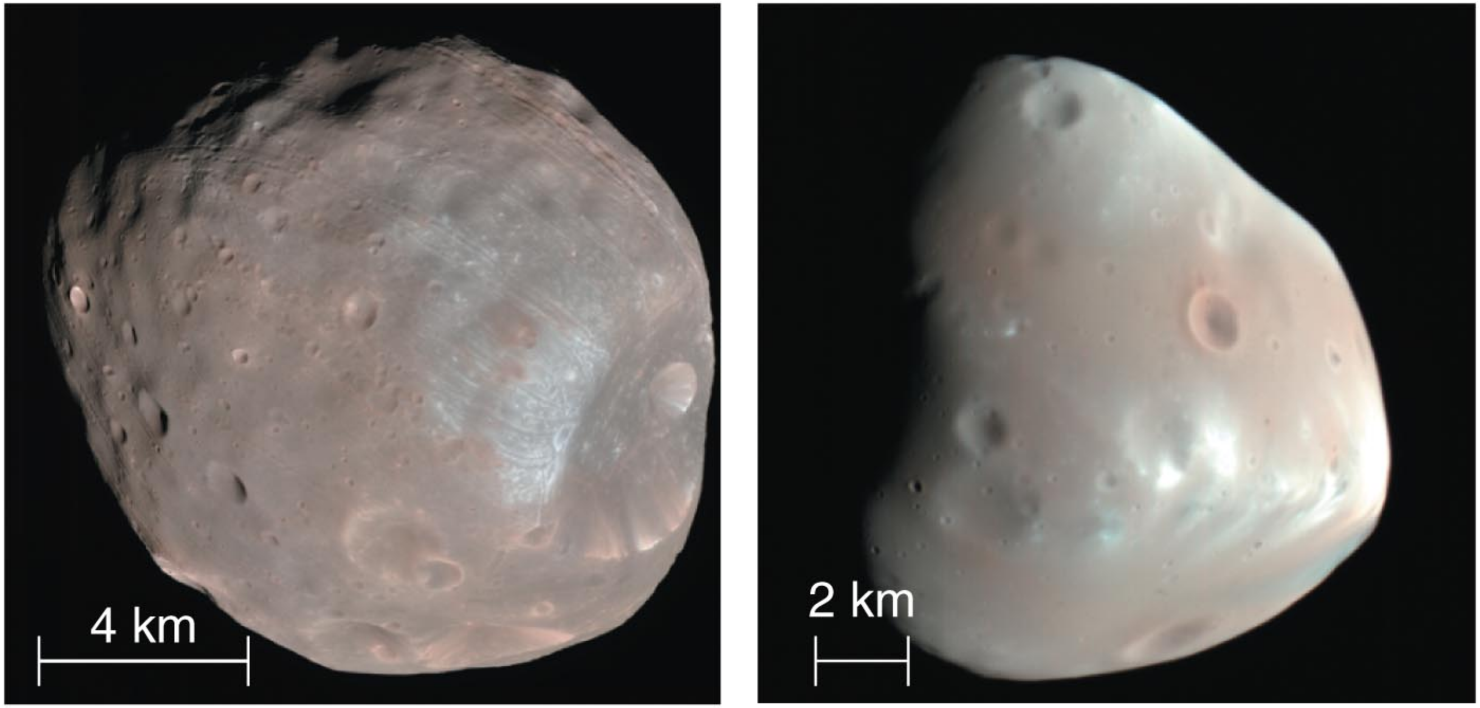
# Origin of Earth's Water



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

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

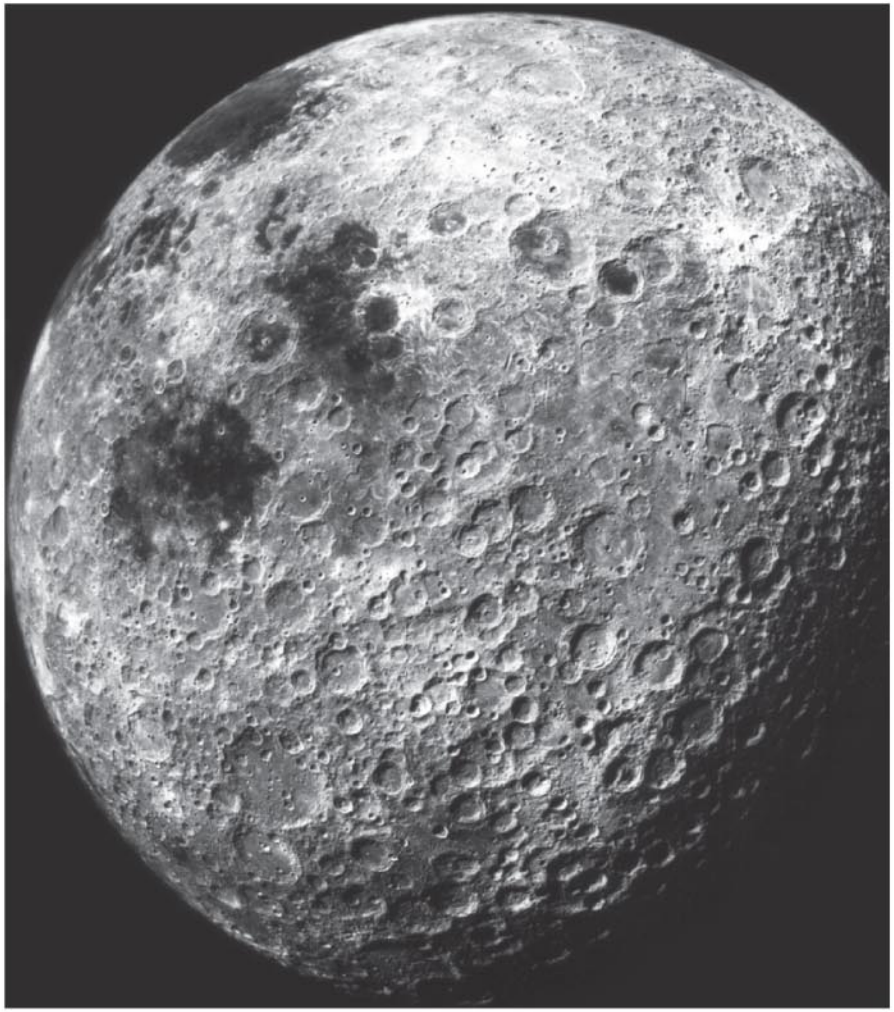
# Captured Moons




a Phobos    b Deimos

- Unusual moons of some planets may be captured planetesimals.

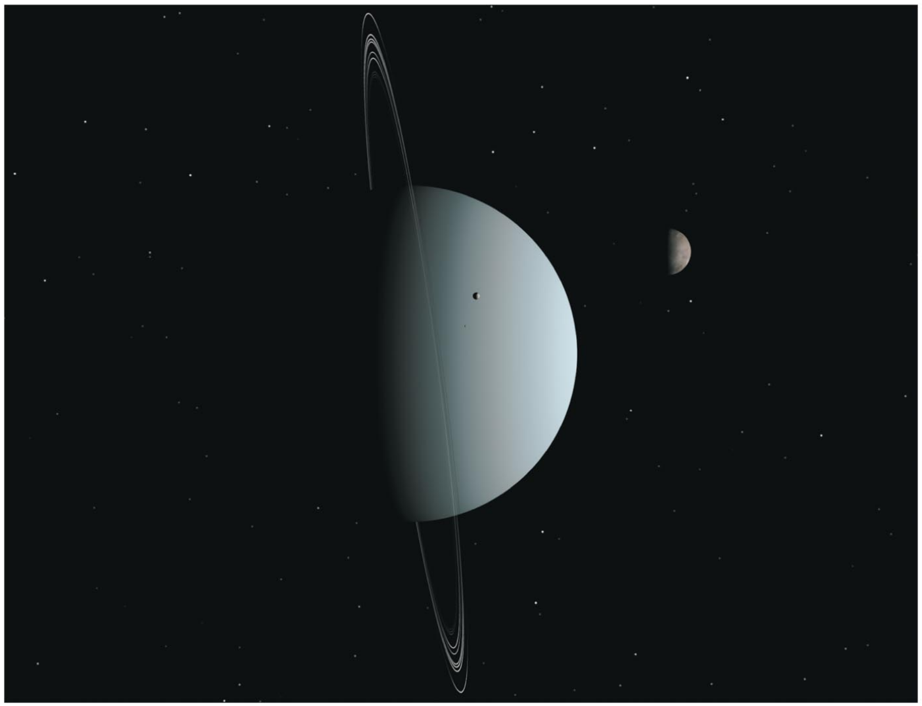
# How do we explain the existence of our Moon?



**a** This *Apollo* photograph of the Moon shows that some areas are much more heavily cratered than others. (This view of the Moon is *not* the one we see from Earth.)

# Giant Impact

# 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?

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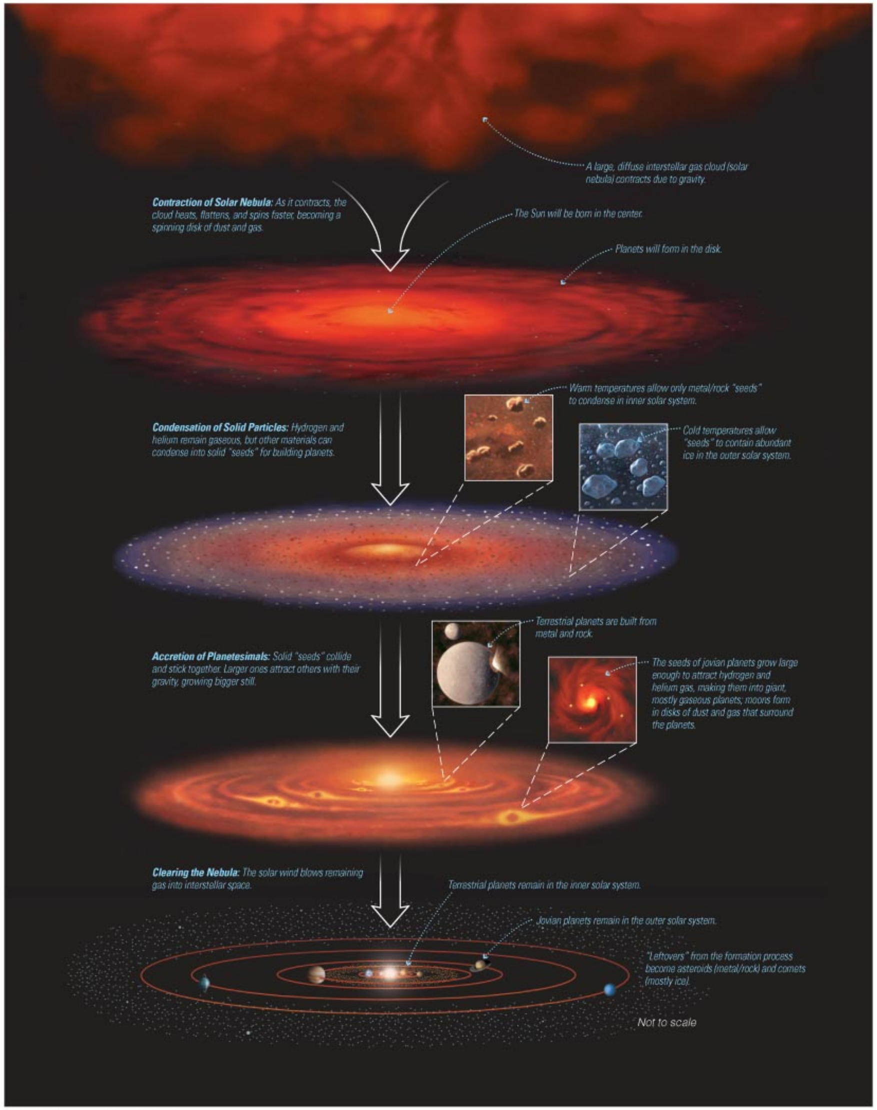
# Was our solar system destined to be?




- Formation of planets in the solar nebula seems inevitable.
- But details of individual planets could have been different.

# 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 same direction and plane.
c) Existence of asteroids and comets.
d) Number of planets of each type (four terrestrial and four jovian).

# 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 same direction and plane.
c) Existence of asteroids and comets.
d) **Number of planets of each type (four terrestrial and four jovian).**

# 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.

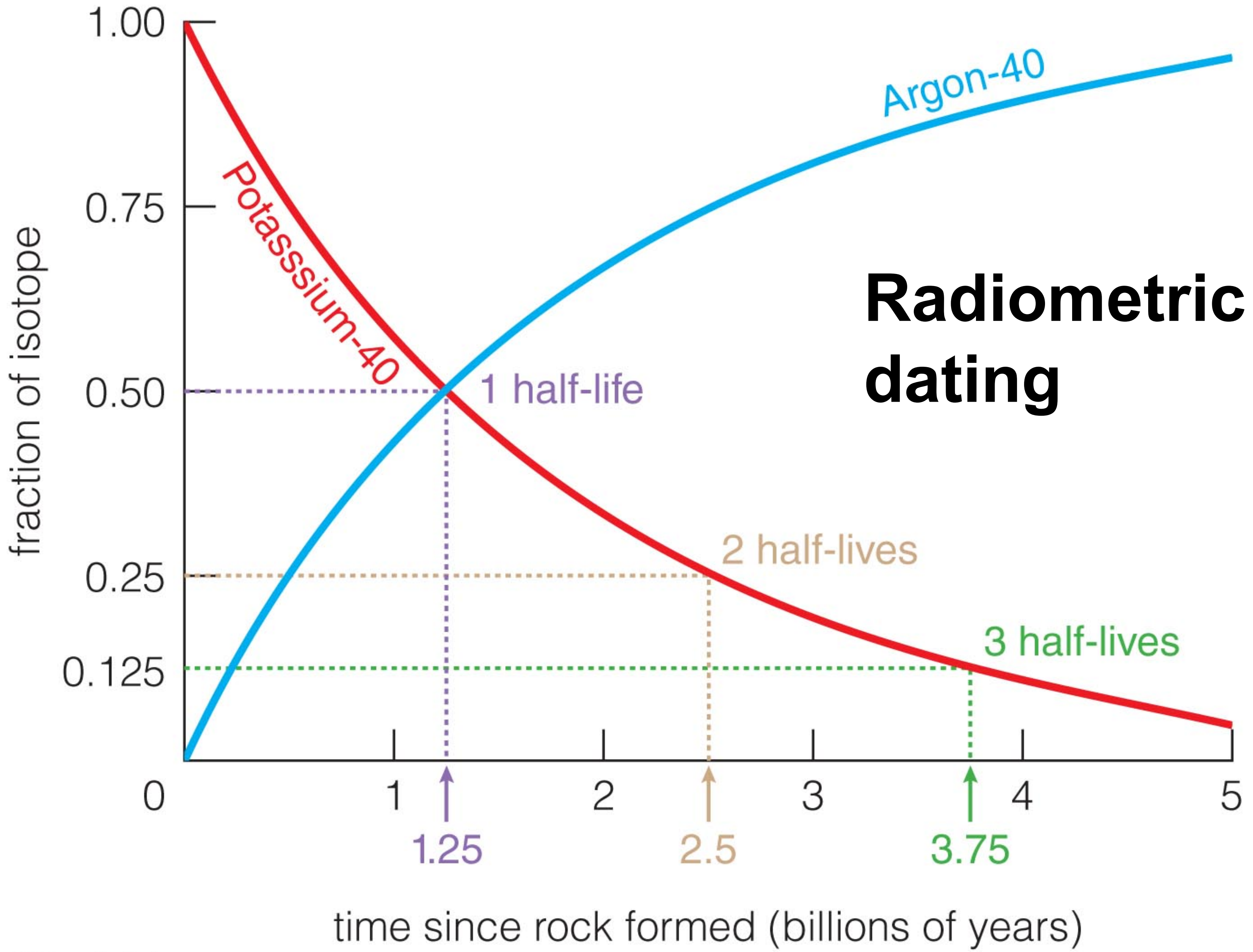
# What have we learned?

- **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.

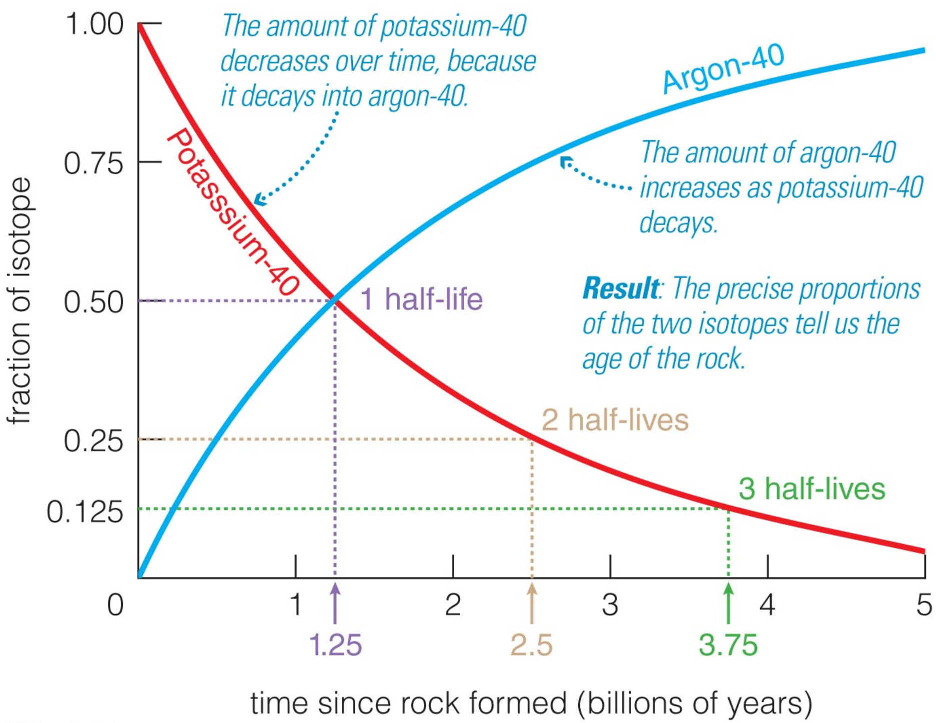
# 8.3 The Age of the Solar System

- 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

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a) 1.25 billion years ago
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c) 3.75 billion years ago
**d) 5 billion years ago**

# Quick calculation

| Time (billion years) | Potassium-40 | Argon-40 | Balance ($^{40}Ar$ : $^{40}K$) |
|---|---|---|---|
| 0 | 1/1 | 0 | 0 |
| 1.25 | ½ | ½ | 1 : 1 |
| 2.50 | ½ - ¼ = ¼ | ½ + ¼ = ¾ | 3 : 1 |
| 3.75 | $^1/_4 - ^1/_8 = ^1/_8$ | $^3/_4 + ^1/_8 = ^7/_8$ | 7 : 1 |
| 5.0 | $^1/_8 - ^1/_{16} = ^1/_{16}$ | $^7/_8 + ^1/_{16} = ^{15}/_{16}$ | 15 : 1 |

# 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 the age of rock.
- **How do we know the age of the solar system?**
  - Radiometric dating indicates that planets formed 4.5 billion years ago.