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Chapter 8
Origin of the Solar System and Extrasolar Planets

- The solar system is our home in the universe.
  - As humans are an intelligent species, we have the right and the responsibility to wonder what we are.
  - Our kind has inhabited this solar system for at least a million years.
  - However, only within the last hundred years have we begun to understand what a solar system is.

The Great Chain of Origins

- You are linked through a great chain of origins that leads backward through time to the first instant when the universe began 13.7 billion years ago.
  - The gradual discovery of the links in that chain is one of the most exciting adventures of the human intellect.

The Great Chain of Origins

- Earlier, you have studied some of that story:
  - Origin of the universe in the big bang
  - Formation of galaxies
  - Origin of stars
  - Production of the chemical elements
- Here, you will explore further and consider the origin of planets.

The History of the Atoms in Your Body

- By the time the universe was three minutes old, the protons, neutrons, and electrons in your body had come into existence.
  - You are made of very old matter.

The History of the Atoms in Your Body

- Although those particles formed quickly, they were not linked together to form the atoms that are common today.
  - Most of the matter was hydrogen and about 25 percent was helium.
  - Very few of the heavier atoms were made in the big bang.

The History of the Atoms in Your Body

- Although your body does not contain helium, it does contain many of those ancient hydrogen atoms that have remained unchanged since the universe began.

The History of the Atoms in Your Body

- During the first few hundred million years after the big bang, matter collected to form galaxies containing billions of stars.
  - You have learned how nuclear reactions inside stars combine low-mass atoms, such as hydrogen, to make heavier atoms.

The History of the Atoms in Your Body

- Generation of stars cooked the original particles, fusing them into atoms such as carbon, nitrogen, and oxygen.
  - Those are common atoms in your body.
  - Even the calcium atoms in your bones were assembled inside stars.

The History of the Atoms in Your Body

- Most of the iron in your body was produced by:
  - Carbon fusion in type Ia supernovae
  - Decay of radioactive atoms in the expanding matter ejected by type II supernovae

The History of the Atoms in Your Body

- Atoms heavier than iron, such as iodine, were created by:
  - Rapid nuclear reactions that can occur only during supernova explosions

The History of the Atoms in Your Body

- Elements uncommon enough to be expensive—gold, silver, and platinum in the jewelry that humans wear—also were produced:
  - during the violent deaths of rare, massive stars.

The History of the Atoms in Your Body

- Our galaxy contains at least 100 billion stars, of which the sun is one.
  - The sun formed from a cloud of gas and dust about 5 billion years ago.
  - The atoms in your body were part of that cloud.

The History of the Atoms in Your Body

- How the sun took shape, how the cloud gave birth to the planets, and how the atoms in your body found their way onto Earth and into you is the story of this chapter.

The History of the Atoms in Your Body

- As you explore the origin of our solar system, you should keep in mind the great chain of origins that created the atoms.
  - As the geologist Preston Cloud remarked, "Stars have died that we might live."

The Origin of the Solar System

- Astronomers have a theory for the origin of our solar system that is consistent both with observations of the solar system and with observations of star formation.
  - Now, they are refining the details.

The Origin of the Solar System

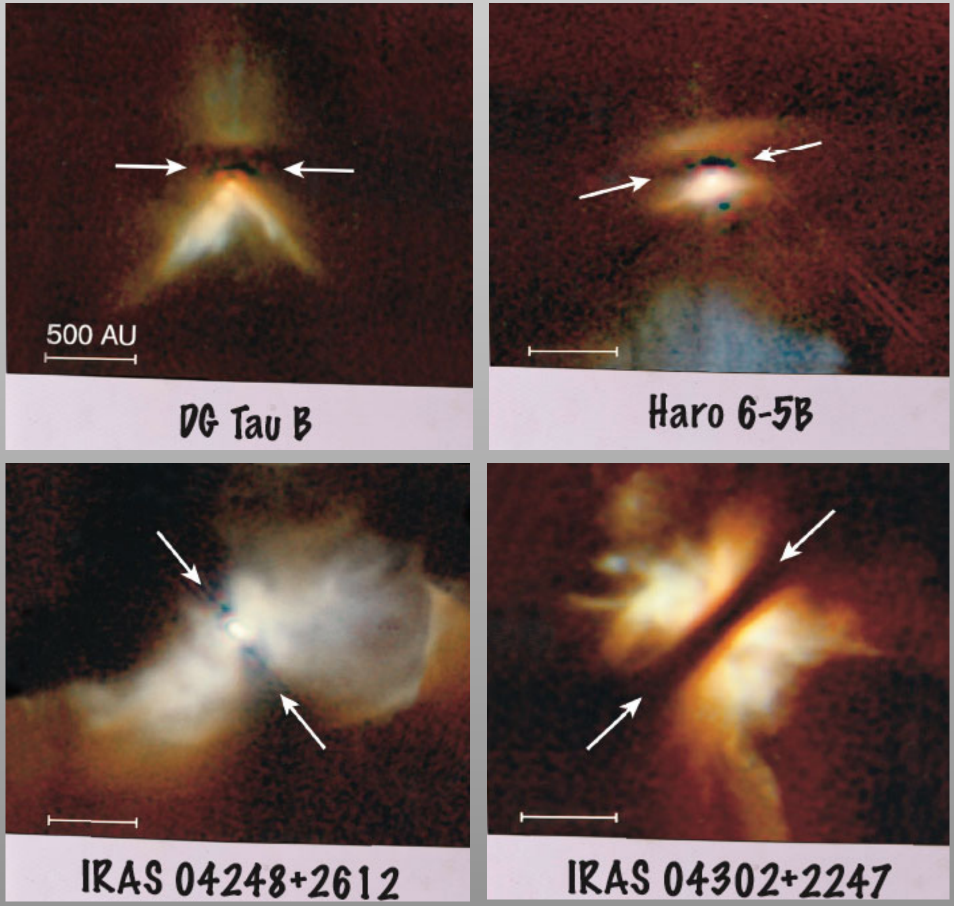
- The solar nebula theory supposes that:
  - Planets form in the rotating disks of gas and dust around young stars.

The Origin of the Solar System

- There is clear evidence that disks of gas and dust are common around young stars.
- The idea is so comprehensive and explains so many observations that it can be considered to have 'graduated' from being just a hypothesis to being properly called a theory.
  - –Bipolar flows from protostars were the first evidence of such disks.

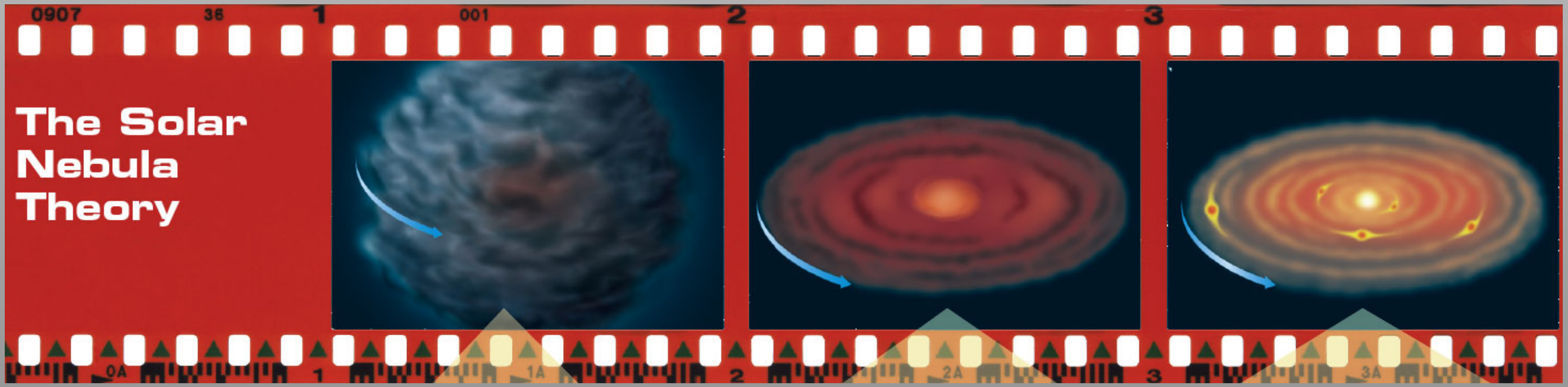
The Origin of the Solar System

- Modern techniques, though, can image the disks directly.



The Origin of the Solar System

- Our own planetary system formed in such a disk-shaped cloud around the sun.
  - When the sun became luminous enough, the remaining gas and dust were blown away into space—leaving the planets orbiting the sun.



The Origin of the Solar System

- According to the solar nebula hypothesis, Earth and the other planets of the solar system formed billions of years ago as the sun condensed from the interstellar medium.

The Origin of the Solar System

- The theory predicts that most stars should have planets because planet formation is a natural part of star formation.
  - Therefore, planets should be very common in the universe—probably more common than stars.

A Survey of the Planets

- To explore consequences of the solar nebula theory, astronomers search the present solar system for evidence of its past.
- You should begin with the most general view of the solar system.
  - It is almost entirely empty space.

A Survey of the Planets

- Imagine that you reduce the solar system until Earth is the size of a grain of table salt—about 0.3 mm (0.01 in.) in diameter.
  - The sun is the size of a small plum 4 m (13 ft) from Earth.
  - Jupiter is an apple seed 20 m (66 ft) from the sun.
  - Neptune, at the edge of the solar system, is a large grain of sand located 120 m (400 ft) from the central plum.

A Survey of the Planets

- You can see that planets are tiny specks of matter scattered around the sun—the last significant remains of the solar nebula.

Revolution and Rotation

- The planets revolve around the sun in orbits that lie close to a common plane.
  - The orbit of Mercury, the planet closest to the sun, is tipped 7.0° to Earth's orbit.
  - The rest of the planets' orbital planes are inclined by no more than 3.4°.
  - Thus, the solar system is basically 'flat' and disk-shaped.

Revolution and Rotation

- The rotation of the sun and planets on their axes also seems related to the same overall direction of motion.
  - The sun rotates with its equator inclined only 7.2° to Earth’s orbit.
  - Most of the other planets’ equators are tipped less than 30°.

Revolution and Rotation

- However, the rotations of Venus and Uranus are peculiar.
  - Compared with the other planets, Venus rotates backward.
  - Uranus rotates on its sides—with the equator almost perpendicular to its orbit.

Revolution and Rotation

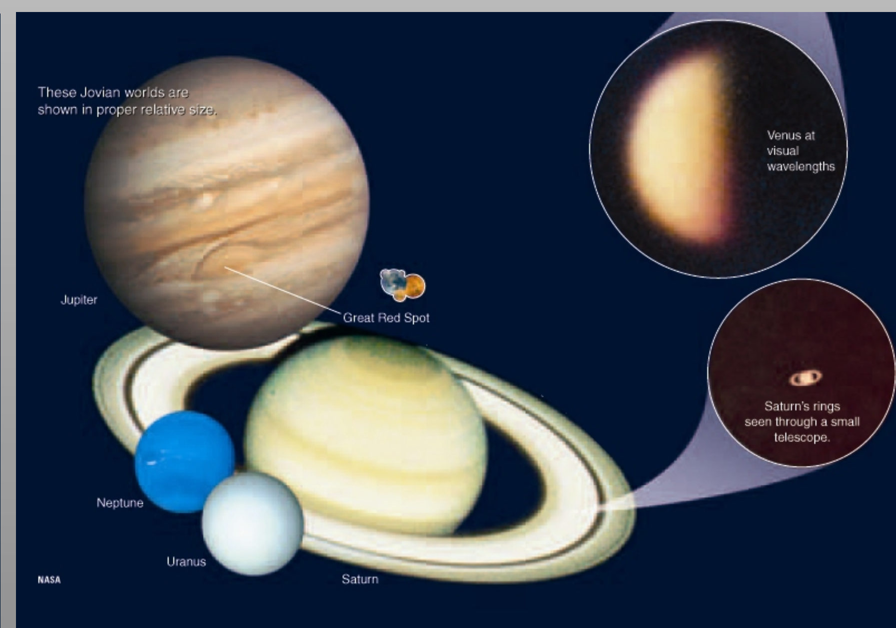
- Apparently, the preferred direction of motion in the solar system (counterclockwise as seen from the north) is also related to the rotation of a disk of material that became the planets.
  - All the planets revolve around the sun in that direction.
  - Venus and Uranus are exceptions—they rotate on their axes in that same direction.

Revolution and Rotation

- Furthermore, nearly all the moons in the solar system, including Earth's moon, orbit around their planets counterclockwise.
  - With only a few exceptions, most of which are understood, revolution and rotation in the solar system follow a common theme.

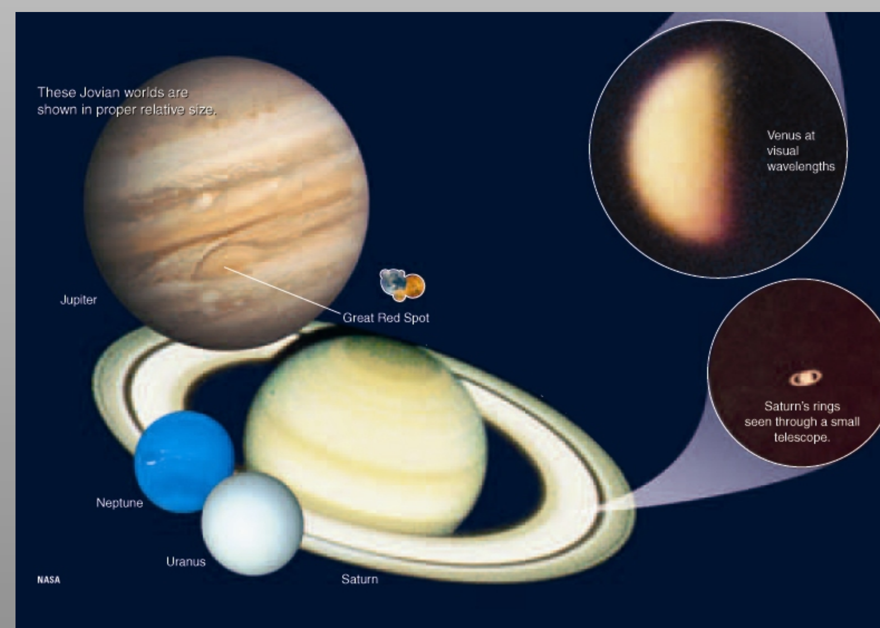
Two Kinds of Planets

- Perhaps the most striking clue to the solar system's origin comes from the obvious division of the planets into two categories:
  - The small Earthlike worlds
  - The giant Jupiterlike worlds



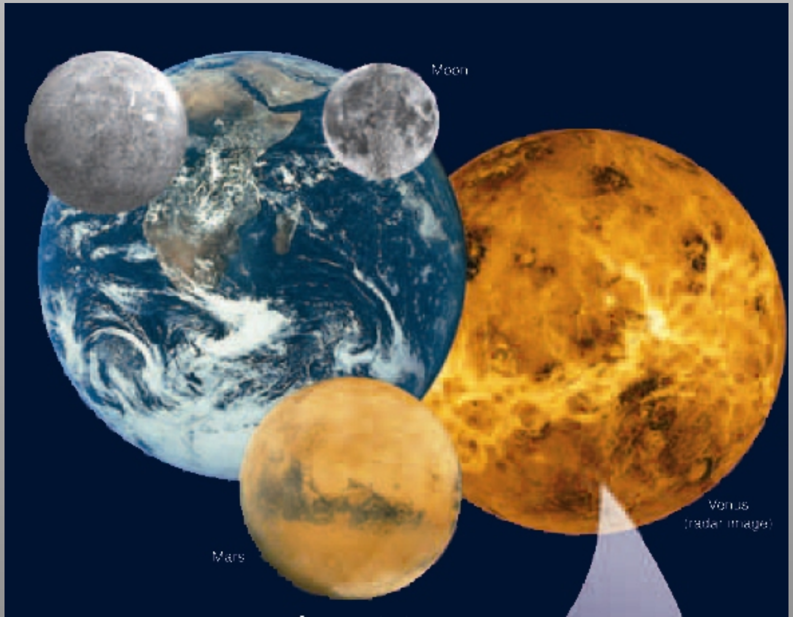
Two Kinds of Planets

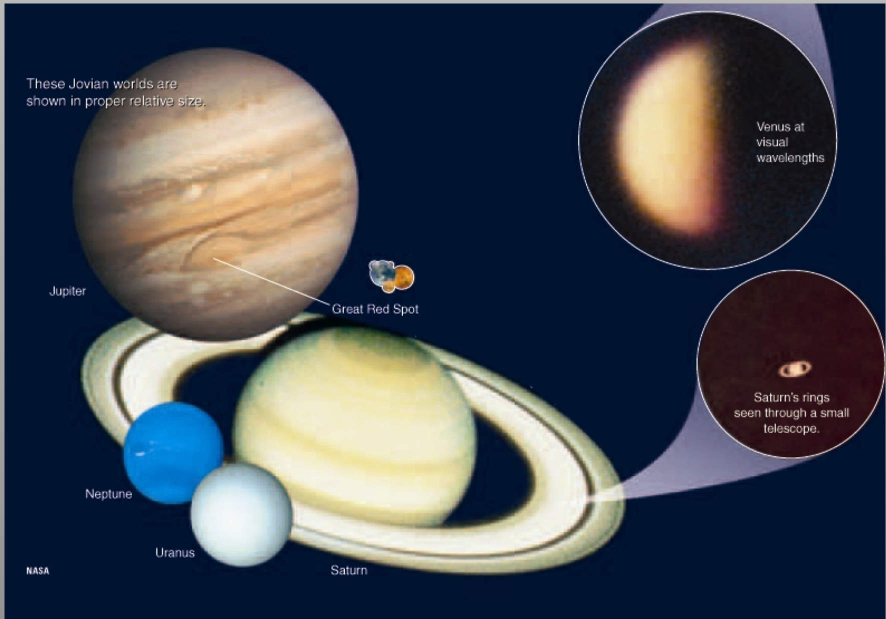
- The difference is so dramatic that you are led to say, "Aha, this must mean something!"



Two Kinds of Planets

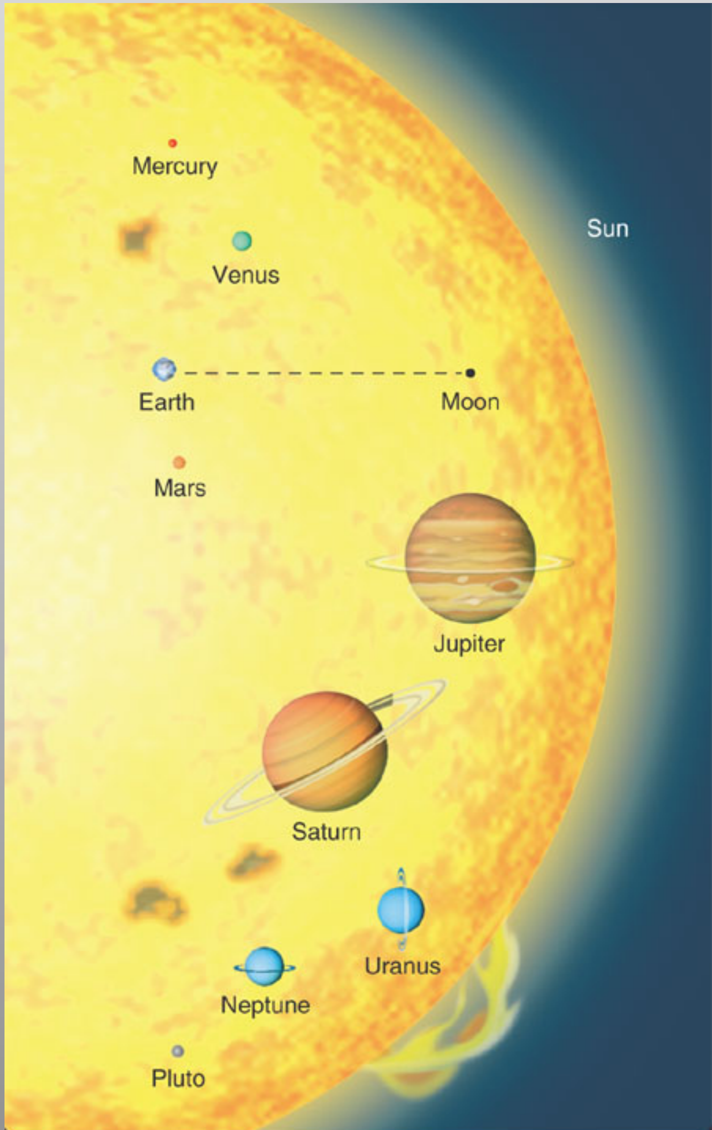
- There are three important points to note about these categories.





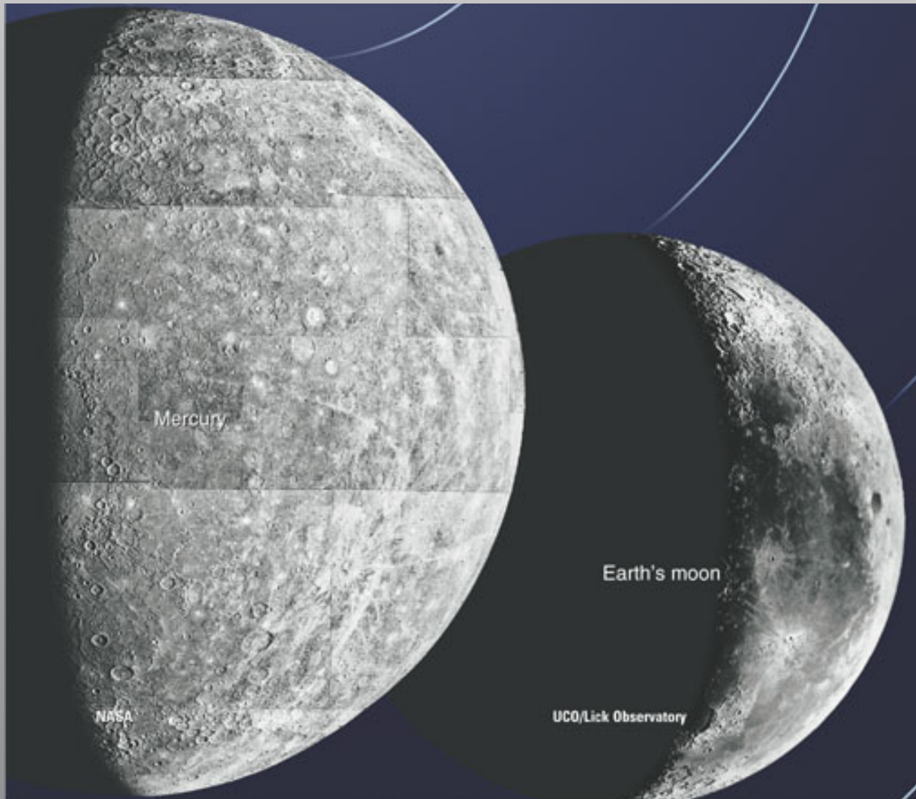
Two Kinds of Planets

- One, they are distinguished by their location.
  - The four inner planets are quite different from the outer four.



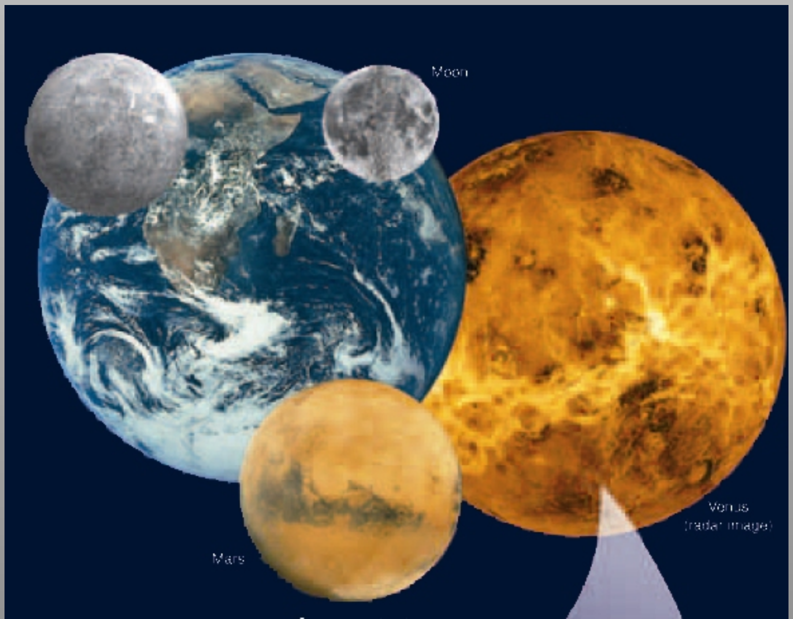
Two Kinds of Planets

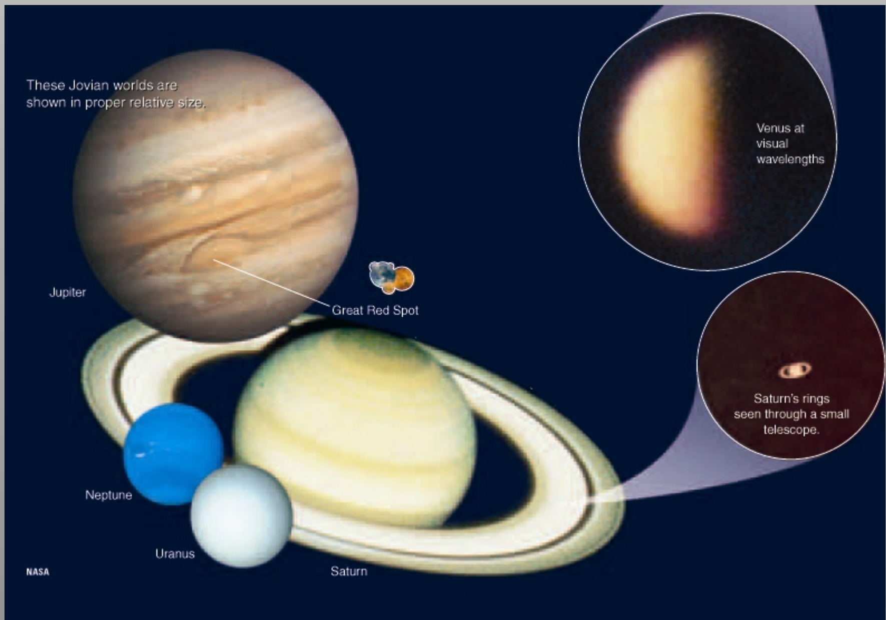
- Two, almost every solid surface in the solar system is covered with craters.



Two Kinds of Planets

- Three, the planets are distinguished by individual properties such as rings, clouds, and moons.
  - Any theory of the origin of the planets needs to explain these properties.





Two Kinds of Planets

- The division of the planets into two families is a clue to how our solar system formed.
  - The present properties of individual planets, however, don't reveal everything you need to know about their origins.
  - The planets have all evolved since they formed.

Two Kinds of Planets

- For further clues, you can look at smaller objects that have remained largely unchanged since the birth of the solar system.

Space Debris: Planet Building Blocks

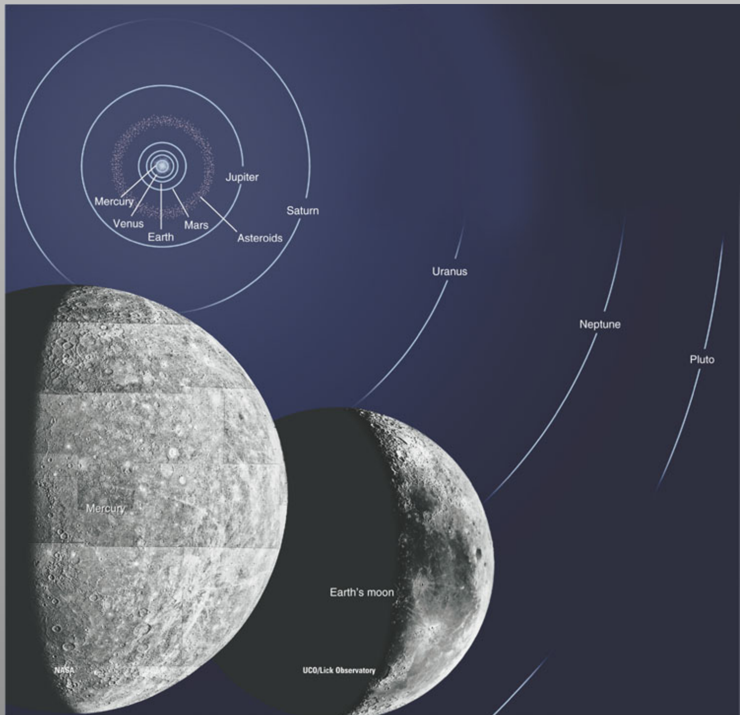
- The solar system is littered with three kinds of space debris:
  - Asteroids
  - Comets
  - Meteoroids

Space Debris: Planet Building Blocks

- Although these objects represent a tiny fraction of the mass of the system, they are a rich source of information about the origin of the planets.

Asteroids

- The asteroids, sometimes called minor planets, are small rocky worlds.
- Most of them orbit the sun in a belt between the orbits of Mars and Jupiter.
  - Roughly 20,000 asteroids have been charted.



Asteroids

- About 2,000 follow orbits that bring them into the inner solar system—where they can occasionally collide with a planet.
  - Earth has been struck many times in its history.

Asteroids

- Other asteroids share Jupiter’s orbit.
- Some others have been found beyond the orbit of Saturn.

Asteroids

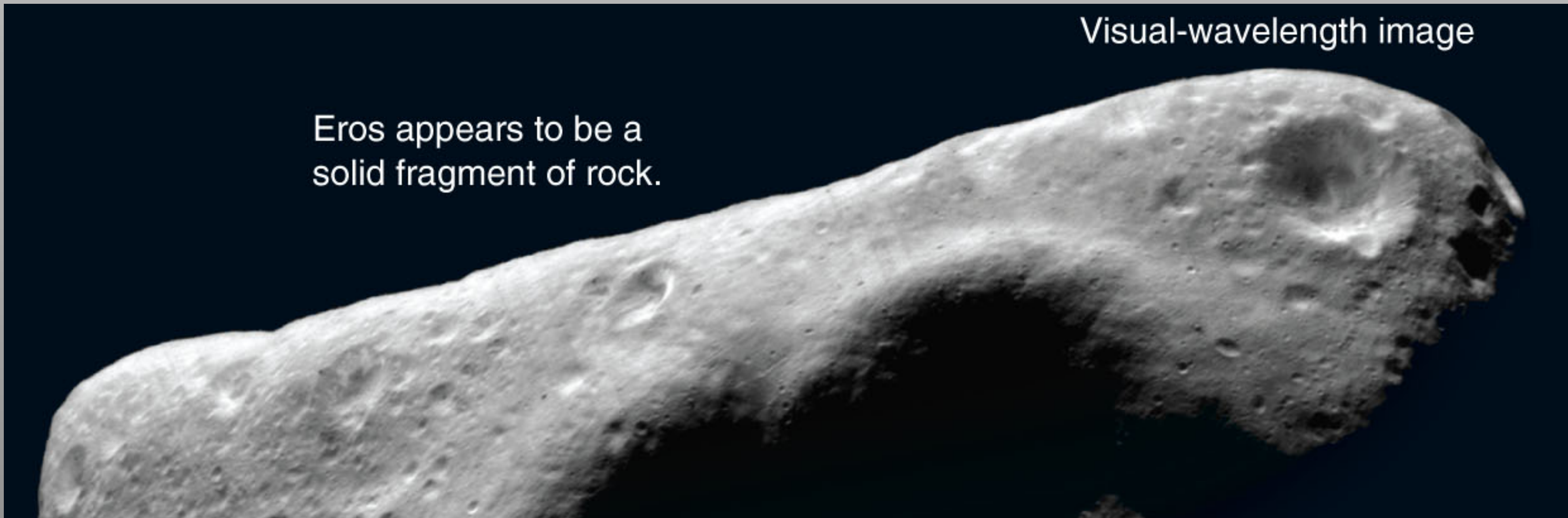
- About 200 asteroids are more than 100 km (60 mi) in diameter.
- Tens of thousands are estimated to be more than 10 km (6 mi) in diameter.
- There are probably a million or more that are larger than 1 km (0.6 mi) and billions that are smaller.

Asteroids

- As even the largest are only a few hundred kilometers in diameter, Earth-based telescopes can detect no details on their surfaces.
  - The Hubble Space Telescope can image only the largest features.

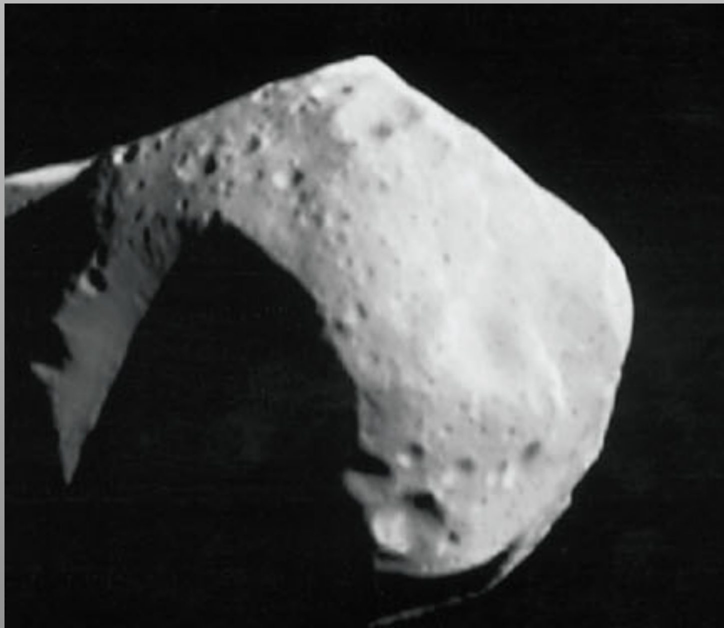
Asteroids

- Photos returned by robotic spacecraft and space telescopes show that asteroids are generally irregular in shape and battered by impact cratering.



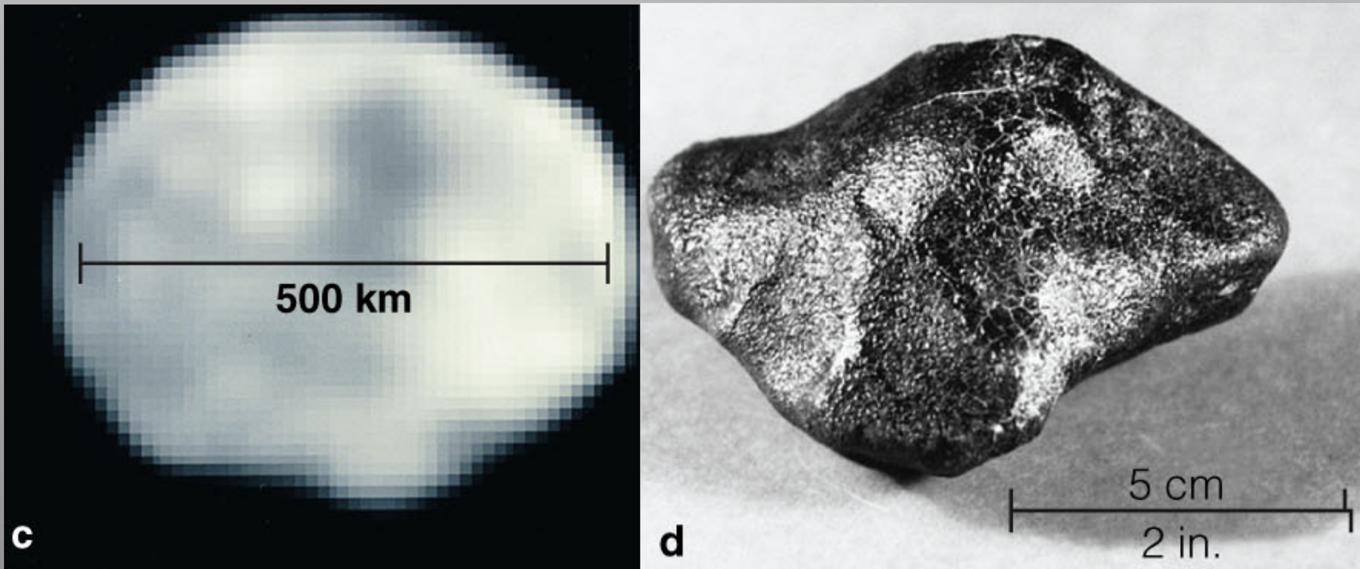
Asteroids

- Some asteroids appear to be rubble piles of broken fragments.
- A few are known to be double objects or to have small moons in orbit around them.
  - These are understood to be evidence of multiple collisions among the asteroids.



Asteroids

- A few larger asteroids show signs of volcanic activity on their surfaces that may have happened when the asteroid was young.



Asteroids

- Astronomers recognize the asteroids as debris left over by a planet that failed to form at a distance of about 3 AU from the sun.
  - A good theory should explain why a planet failed to form there, leaving behind a belt of construction material.

Comets

- In contrast to the rocky asteroids, the brightest comets are impressively beautiful objects.
  - However, most comets are faint and are difficult to locate even at their brightest.

Comets

- A comet may take months to sweep through the inner solar system.
- During this time, it appears as a glowing head with an extended tail of gas and dust.

Comets

- The beautiful tail of a comet can be longer than 1 AU.
- However, it is produced by an icy nucleus only a few tens of kilometers in diameter.

Comets

- The nucleus remains frozen and inactive while it is far from the sun.
  - As the nucleus moves along its elliptical orbit into the inner solar system, the sun’s heat begins to vaporize the ices—releasing gas and dust.

Comets

- The pressure of sunlight and solar wind push the gas and dust away, forming a long tail.

Comets

- The gas and dust respond differently to the forces acting on them.
- So, they sometimes separate into two separate sub-tails.

Comets

- The motion of the nucleus along its orbit, the pressure of sunlight, and the outward flow of the solar wind cause the tails to point always approximately away from the sun.

Comets

- Comet nuclei contain:
  - Ices of water
  - Other volatile compounds such as carbon dioxide, methane, and ammonia

Comets

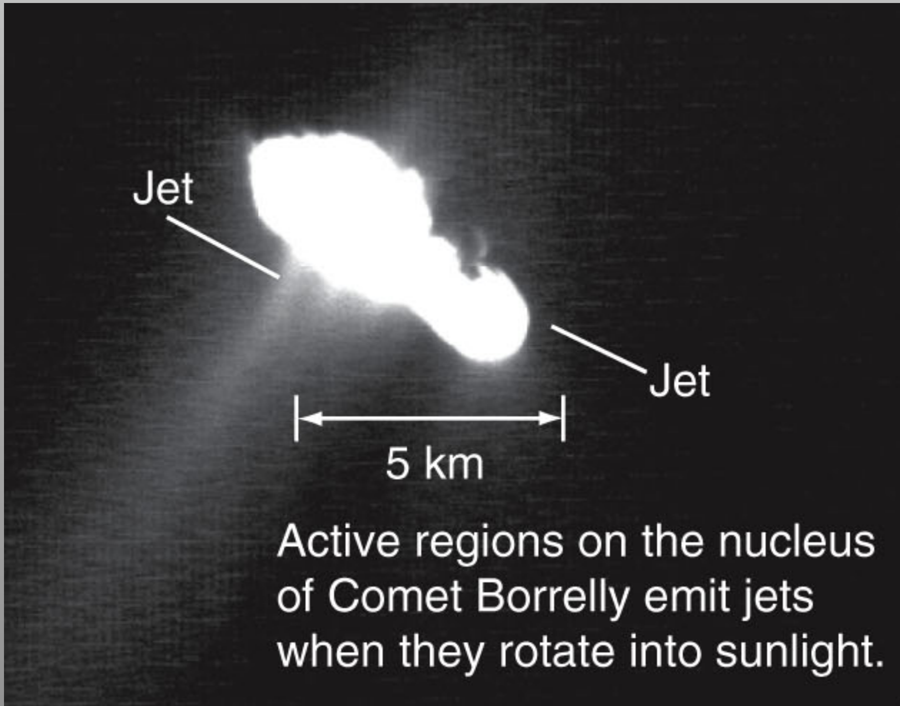
- These ices are the kinds of compounds that should have condensed from the outer solar nebula.
  - That makes astronomers think that comets are ancient samples of the gases and dust from which the outer planets formed.

Comets

- Five spacecraft flew past the nucleus of Comet Halley when it visited the inner solar system in 1985 and 1986.
  - Since then, spacecraft have visited the nuclei of several other comets.

Comets

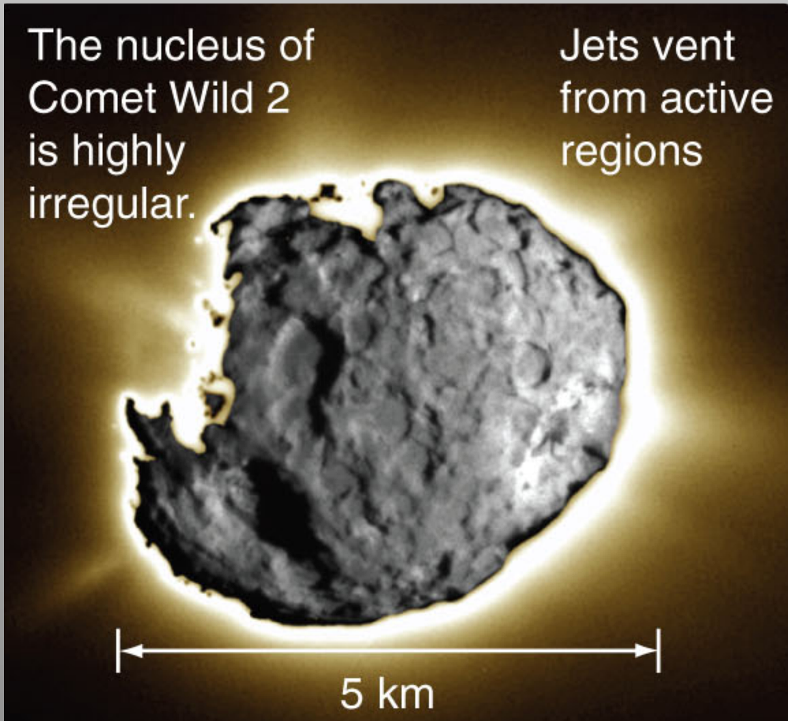
- Images show that comet nuclei are irregular in shape and very dark, with jets of gas and dust spewing from active regions on the nuclei.



Active regions on the nucleus of Comet Borrelly emit jets when they rotate into sunlight.

Comets

- In general, these nuclei are darker than a lump of coal.
  - This suggests that they have composition similar to certain dark, water- and carbon-rich meteorites.



Comets

- Since 1992, astronomers have discovered roughly a thousand small, dark, icy bodies orbiting in the outer fringes of the solar system beyond Neptune.

Comets

- This collection of objects is called the Kuiper belt.
  - It is named after the Dutch-American astronomer Gerard Kuiper, who predicted their existence in the 1950s.

Comets

- There are probably 100 million bodies larger than 1 km in the Kuiper belt.
  - Any successful theory should explain how they came to be where they are.

Comets

- Astronomers believe that some comets, those with the shortest orbital periods and orbits in the plane of the solar system, come from the Kuiper belt.

Meteoroids, Meteors, and Meteorites

- Unlike the stately comets, meteors flash across the sky in momentary streaks of light.
  - They are commonly called “shooting stars.”

Meteoroids, Meteors, and Meteorites

- They are not stars but small bits of rock and metal falling into Earth’s atmosphere.
  - They burst into incandescent vapor about 80 km (50 mi) above the ground because of friction with the air.
  - This hot vapor condenses to form dust, which settles slowly to the ground—adding about 40,000 tons per year to the planet’s mass.

Meteoroids, Meteors, and Meteorites

- Technically, the word *meteor* refers to the streak of light in the sky.
- In space, before its fiery plunge, the object is called a meteoroid.

Meteoroids, Meteors, and Meteorites

- Most meteoroids are specks of dust, grains of sand, or tiny pebbles.
  - Almost all the meteors you see in the sky are produced by meteoroids that weigh less than 1 g.
  - Only rarely is one massive enough and strong enough to survive its plunge, reach Earth's surface, and become what is called a meteorite.

Meteoroids, Meteors, and Meteorites

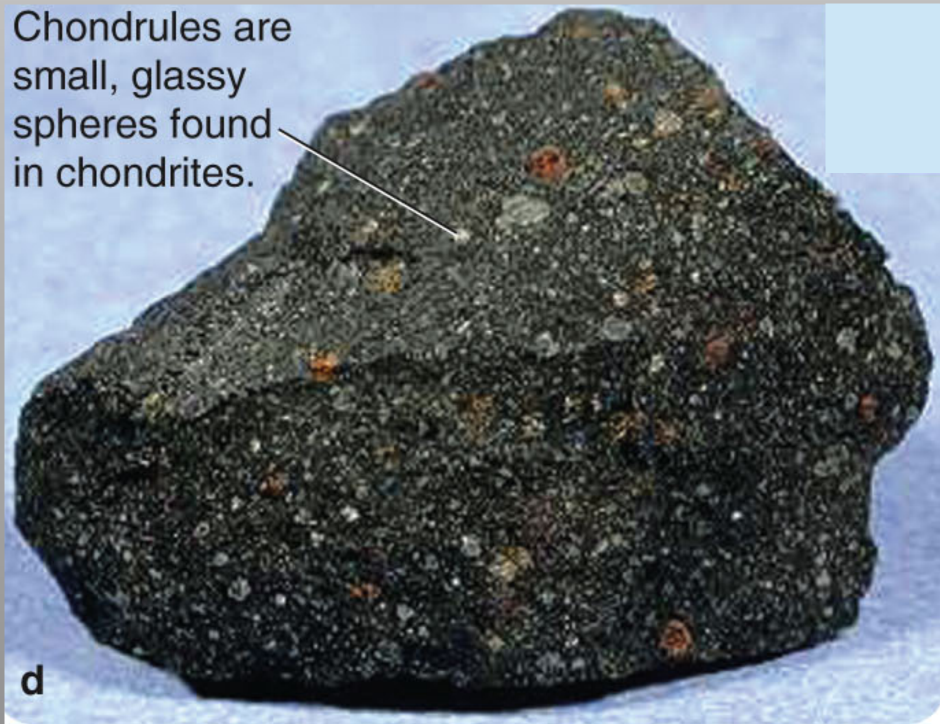
- Meteorites can be divided into three broad categories.
  - *Iron*
  - *Stony*
  - *Stony-iron*

Meteoroids, Meteors, and Meteorites

- Iron meteorites are solid chunks of iron and nickel.
- Stony meteorites are silicate masses that resemble Earth rocks.
- Stony-iron meteorites are iron-stone mixtures.

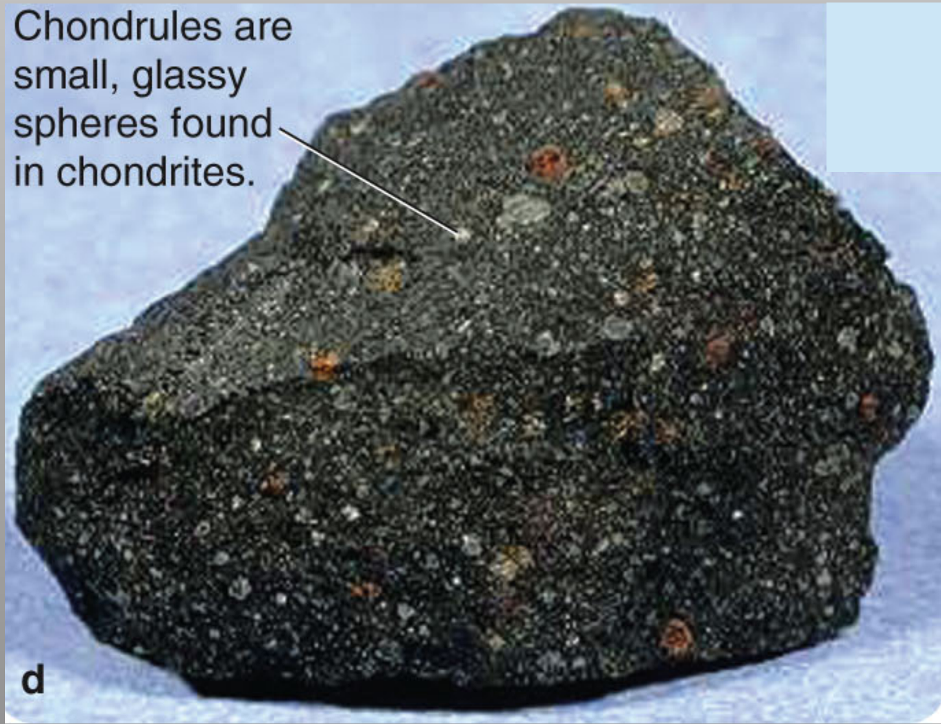
Meteoroids, Meteors, and Meteorites

- One type of stony meteorite called carbonaceous chondrites has a chemical composition that resembles a cooled lump of the sun with the hydrogen and helium removed.



Meteoroids, Meteors, and Meteorites

- These meteorites generally contain abundant volatile compounds including significant amounts of carbon and water.
  - They may have similar composition to comet nuclei.

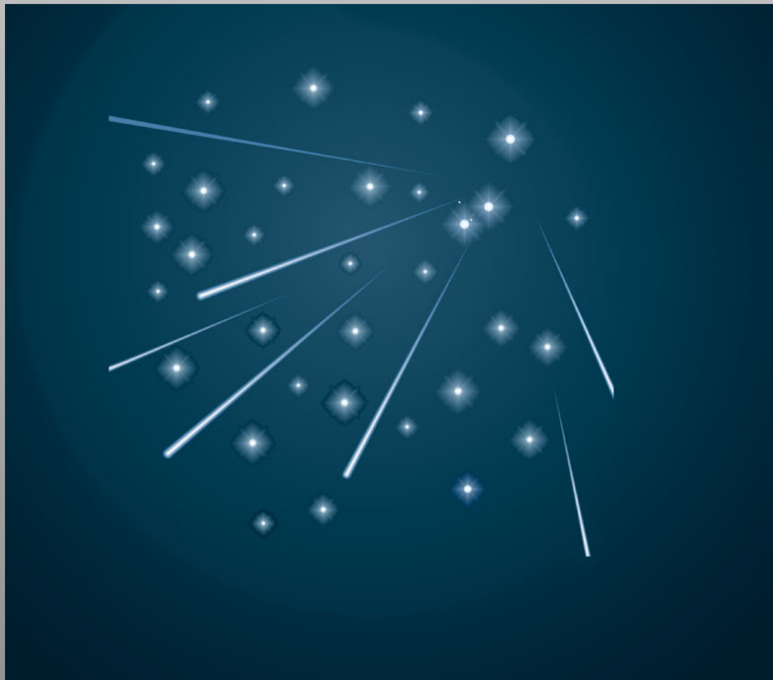


Meteoroids, Meteors, and Meteorites

- Heating would have modified and driven off these fragile compounds.
- So, carbonaceous chondrites must not have been heated since they formed.
  - Astronomers conclude that carbonaceous chondrites, unlike the planets, have not evolved and thus give direct information about the early solar system.

Meteoroids, Meteors, and Meteorites

- You can find evidence of the origin of meteors through one of the most pleasant observations in astronomy.
  - You can watch a meteor shower, a display of meteors that are clearly related by a common origin.

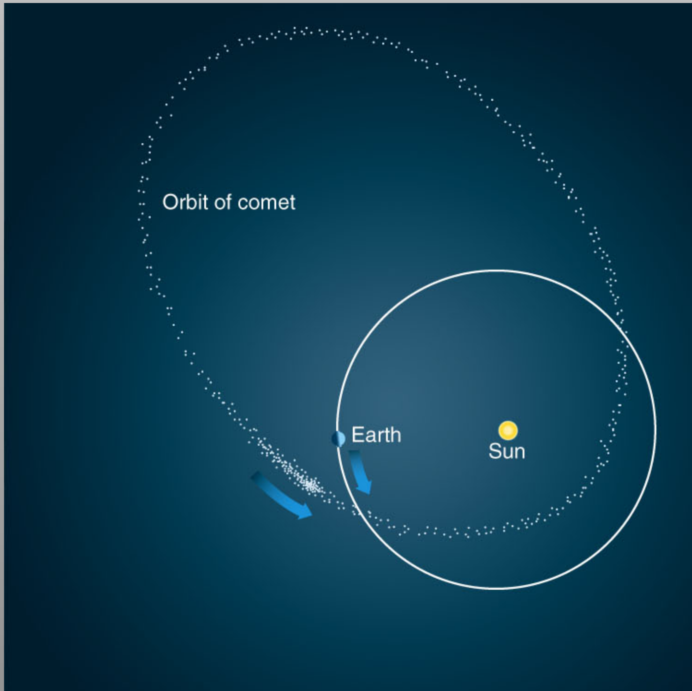


Meteoroids, Meteors, and Meteorites

- For example, the Perseid meteor shower occurs each year in August.
- During the height of the shower, you might see as many as 40 meteors per hour.
  - The shower is so named because all its meteors appear to come from a point in the constellation Perseus.

Meteoroids, Meteors, and Meteorites

- Meteor showers are seen when Earth passes near the orbit of a comet.
- The meteors in meteor showers must be produced by dust and debris released from the icy head of the comet.
  - In contrast, the orbits of some meteorites have been calculated to lead back into the asteroid belt.



The Story of Planet Formation

- An important reason to mention meteorites here is for one specific clue they can give you concerning the solar nebula: Meteorites can reveal the age of the solar system.
- The challenge for modern planetary astronomers is to compare the characteristics of the solar system with the solar nebula theory and tell the story of how the planets formed.

The Age of the Solar System

- According to the solar nebula theory, the planets should be about the same age as the sun.

The Age of the Solar System

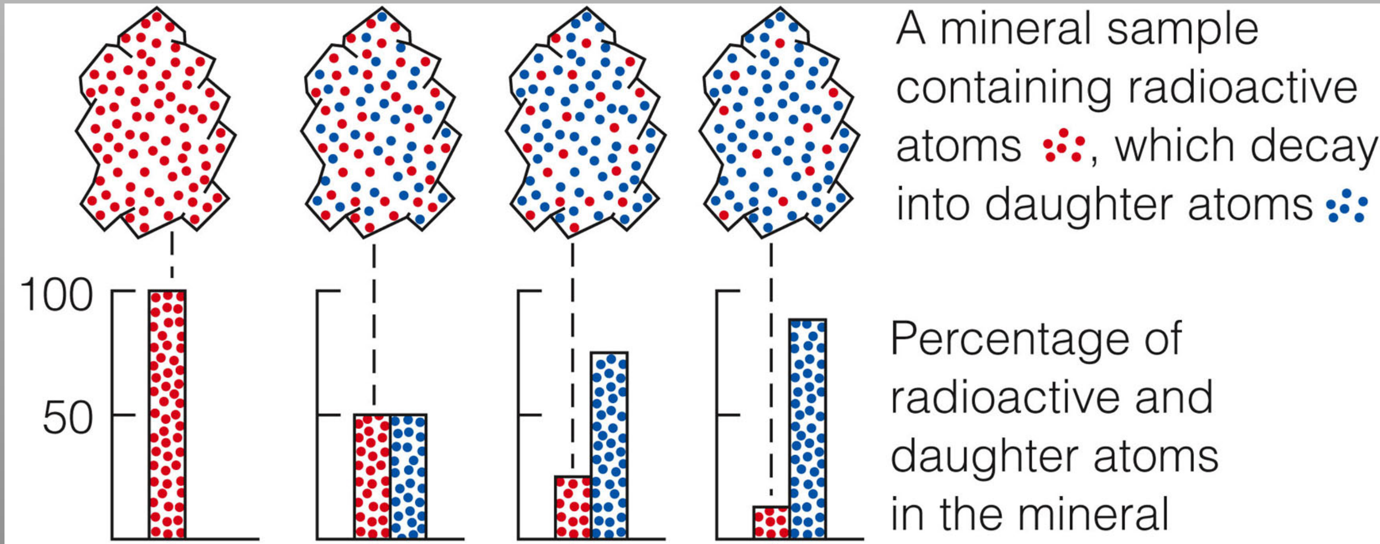
- The most accurate way to find the age of a rocky body is to bring a sample into the laboratory and determine its age by analyzing the radioactive elements it contains.
  - When a rock solidifies, the process of cooling causes it to incorporate known proportions of the chemical elements.

The Age of the Solar System

- A few of those elements are radioactive and can decay into other elements—called daughter elements or isotopes.
- The half-life of a radioactive element is the time it takes for half of the radioactive atoms to decay into the daughter elements.

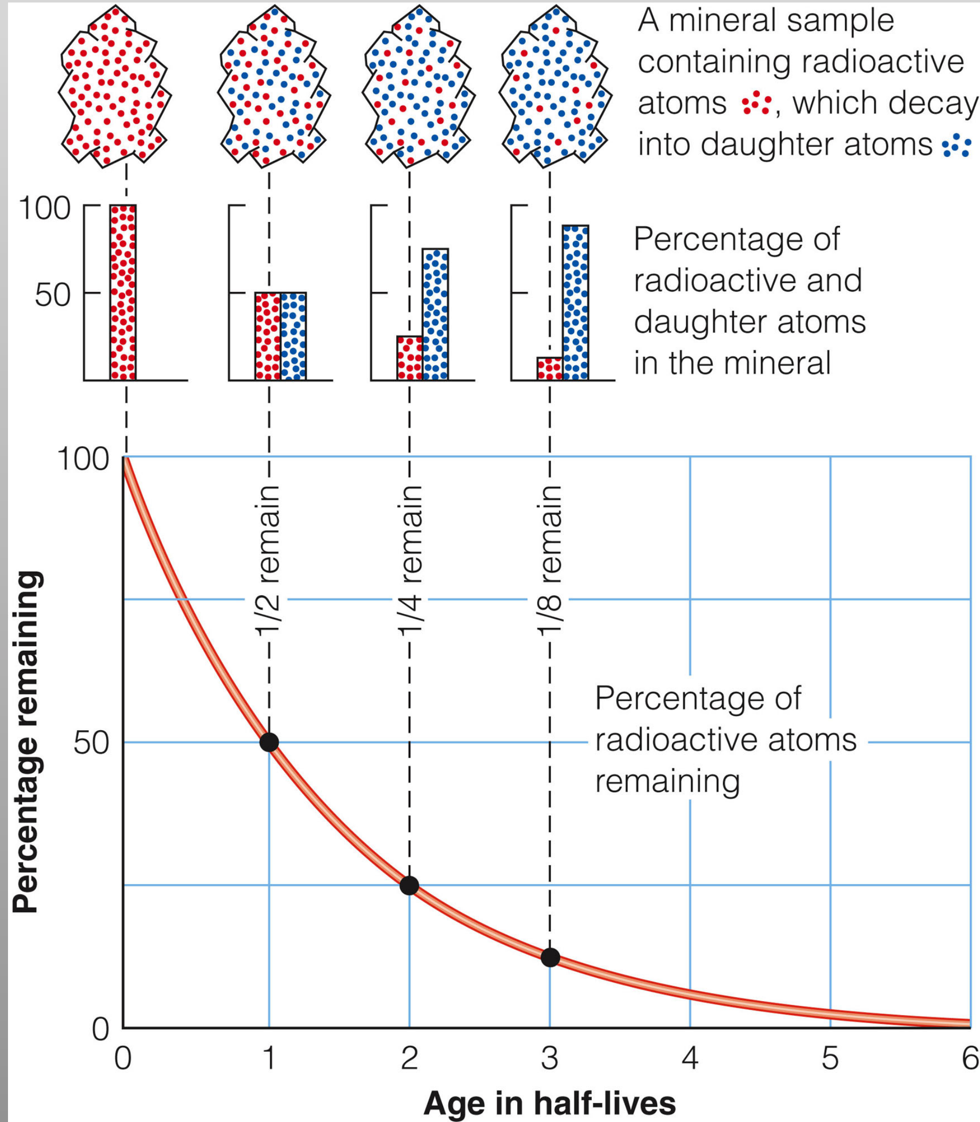
The Age of the Solar System

- For example, potassium-40 decays into daughter isotopes calcium-40 and argon-40 with a half-life of 1.3 billion years.
- Also, uranium-238 decays with a half-life of 4.5 billion years to lead-206 and other isotopes.



The Age of the Solar System

- As time passes, the abundance of a radioactive element in a rock gradually decreases, and the abundances of the daughter elements gradually increase.



The Age of the Solar System

- You can estimate the original abundances of the elements in the rock from:
  - Rules of chemistry
  - Observations of rock properties in general

The Age of the Solar System

- Thus, measuring the present abundances of the parent and daughter elements allows you to find the age of the rock.
  - This works best if you have several radioactive element "clocks" that can be used as independent checks on each other.

The Age of the Solar System

- To find a radioactive age, you need a sample in the laboratory.
  - The only celestial bodies from which scientists have samples are Earth, the moon, Mars, and meteorites.

The Age of the Solar System

- The oldest Earth rocks so far discovered and dated are tiny zircon crystals from Australia, 4.4 billion years old.

The Age of the Solar System

- The surface of Earth is active, and the crust is continually destroyed and reformed from material welling up from beneath the crust.
  - The age of these oldest rocks informs you only that Earth is *at least* 4.4 billion years old.

The Age of the Solar System

- Unlike Earth's surface, the moon's surface is not being recycled by constant geologic activity.
  - So, you can guess that more of it might have survived unaltered since early in the history of the solar system.
  - The oldest rocks brought back by the Apollo astronauts are 4.48 billion years old.
  - That means the moon must be at least 4.48 billion years old.

The Age of the Solar System

- Although no one has yet been to Mars, over a dozen meteorites found on Earth have been identified by their chemical composition as having come from Mars.
  - The oldest has an age of approximately 4.5 billion years.
  - Mars must be at least that old.

The Age of the Solar System

- The most important source for determining the age of the solar system is meteorites.
  - Carbonaceous chondrite meteorites have compositions indicating that they have not been heated much or otherwise altered since they formed.
  - They have a range of ages with a consistent and precise upper limit of 4.56 billion years.
  - This is widely accepted as the age of the solar system and is often rounded to 4.6 billion years.

The Age of the Solar System

- That is in agreement with the age of the sun—which is estimated to be 5 billion years plus or minus 1.5 billion years.
  - This has been calculated using mathematical models of the sun's interior that are completely independent of meteorite radioactive ages.
  - Apparently, all the bodies of the solar system formed at about the same time, some 4.6 billion years ago.

Chemical Composition of the Solar Nebula

- Everything astronomers know about the solar system and star formation suggests that the solar nebula was a fragment of an interstellar gas cloud.
  - Such a cloud would have been mostly hydrogen with some helium and minor traces of the heavier elements.

Chemical Composition of the Solar Nebula

- That is precisely what you see in the composition of the sun.
  - Analysis of the solar spectrum shows that the sun is mostly hydrogen, with a quarter of its mass being helium.
  - Only about 2 percent are heavier elements.

Chemical Composition of the Solar Nebula

- Of course, nuclear reactions have fused some hydrogen into helium.
- This, however, happens in the core and has not affected its surface composition.
  - Thus, the composition revealed in its spectrum is essentially the same composition of the solar nebula gases from which it formed.

Chemical Composition of the Solar Nebula

- You can see that same solar nebula composition is reflected in the chemical compositions of the planets.

Chemical Composition of the Solar Nebula

- The composition of the Jovian planets resembles the composition of the sun.
- Furthermore, if you allowed low-density gases to escape from a blob of sun-stuff, the remaining heavier elements would resemble the composition of the other terrestrial planets—as well as meteorites.

Condensation of Solids

- The key to understanding the process that converted the nebular gas into solid matter is:
  - The observed variation in density among solar system objects

Condensation of Solids

- The four inner planets are high-density, terrestrial bodies.
- The outer, Jupiter-like planets are low-density, giant planets.
  - This division is due to the different ways gases are condensed into solids in the inner and outer regions of the solar nebula.

Condensation of Solids

- Even among the terrestrial planets, you find a pattern of slight differences in density.
  - The uncompressed densities—the densities the planets would have if their gravity did not compress them—can be calculated from the actual densities and masses of each planet.

Condensation of Solids

- In general, the closer a planet is to the sun, the higher is its uncompressed density.
  - This density variation is understood to have originated when the solar system first formed solid grains.
  - The kind of matter that is condensed in a particular region would depend on the temperature of the gas there.

Condensation of Solids

- In the inner regions, the temperature seems to have been 1,500 K or so.
  - The only materials that can form grains at this temperature are compounds with high melting points—such as metal oxides and pure metals.
  - These are very dense, corresponding to the composition of Mercury.

Condensation of Solids

- Farther out in the nebula, it was cooler.
  - Silicates (rocky material) could condense.
  - These are less dense than metal oxides and metals, corresponding more to the compositions of Venus, Earth, and Mars.

Condensation of Solids

- Somewhere further from the sun, there was a boundary called the ice line—beyond which the water vapor could freeze to form ice.

Condensation of Solids

- Not much farther out, compounds such as methane and ammonia could condense to form other ices.
  - Water vapor, methane, and ammonia were abundant in the solar nebula.
  - So, beyond the ice line, the nebula was filled with a blizzard of ice particles.
  - Those ices have low densities like the Jovian planets.

Condensation of Solids

- The sequence in which the different materials condense from the gas as you move away from the sun is called the condensation sequence.
  - It suggests that the planets, forming at different distances from the sun, accumulated from different kinds of materials.

Table 12.2 The Condensation Sequence

Temperature (K)	Condensate	Object (Estimated Temperature of Formation; K)
1,500	Metal oxides	Mercury (1,400)
1,300	Metallic iron and nickel	
1,200	Silicates	
1,000	Feldspars	Venus (900)
680	Troilite (FeS)	Earth (600) Mars (450)
175	H_2O ice	Jovian (175)
150	Ammonia–water ice	
120	Methane–water ice	
65	Argon–neon ice	Pluto (65)

Condensation of Solids

- The original chemical composition of the solar nebula should have been roughly the same throughout the nebula.

Condensation of Solids

- The important factor was temperature.
  - The inner nebula was hot, and only metals and rock could condense there.
  - The cold outer nebula could form lots of ices in addition to metals and rocks.
  - The ice line seems to have been between Mars and Jupiter—it separates the formation of the dense terrestrial planets from that of the low-density Jovian planets.

Formation of Planetesimals

- In the development of a planet, three groups of processes operate to collect solid bits of matter—rock, metal, or ices—into larger bodies called planetesimals.
  - Eventually, they build the planets.

Formation of Planetesimals

- The study of planet building is the study of three groups of processes:
  - Condensation
  - Accretion
  - Gravitational collapse

Formation of Planetesimals

- According to the solar nebula theory, planetary development in the solar nebula began with the growth of dust grains.
  - These specks of matter, whatever their composition, grew from microscopic size by two processes—condensation and accretion.

Formation of Planetesimals

- A particle grows by condensation when it adds matter, one atom or molecule at a time, from a surrounding gas.
  - Snowflakes, for example, grow by condensation in Earth's atmosphere.
  - In the solar nebula, dust grains were continuously bombarded by atoms of gas—and some of these stuck to the grains.

Formation of Planetesimals

- Accretion is the sticking together of solid particles.
  - You may have seen accretion in action if you have walked through a snowstorm with big, fluffy flakes.
  - If you caught one of those “flakes” on your mitten and looked closely, you saw that it was actually made up of many tiny, individual flakes.
  - They had collided as they fell and accreted to form larger particles.

Formation of Planetesimals

- Model calculations indicate that, in the solar nebula, the dust grains were on the average no more than a few centimeters apart.
  - So, they collided frequently and accreted into larger particles.

Formation of Planetesimals

- There is no clear distinction between a very large grain and a very small planetesimal.
- However, you can consider an object a planetesimal when its diameter approaches a kilometer or so, like the size of a typical small asteroid or comet.

Formation of Planetesimals

- Objects larger than a centimeter were subject to new processes that tended to concentrate them.
  - For example, collisions with the surrounding gas and with each other would have caused growing planetesimals to settle into a thin disk.
  - This is estimated to have been only about 0.01 AU thick in the central plane of the rotating nebula.
  - This concentration of material would have made further planetary growth more rapid.

Formation of Planetesimals

- Computer models show that the rotating disk of particles should have been gravitationally unstable.
  - It would have been disturbed by spiral density waves—much like those found in spiral galaxies.
  - This would have further concentrated the planetesimals and helped them coalesce into objects up to 100 km (60 mi) in diameter.

Formation of Planetesimals

- Through these processes, the nebula became filled with trillions of solid particles ranging in size from pebbles to small planets.
  - As the largest began to exceed 100 km in diameter, new processes began to alter them.
  - A new stage of planet building began, the formation of protoplanets

Growth of Protoplanets

- The coalescing of planetesimals eventually formed protoplanets—massive objects destined to become planets.
  - As these larger bodies grew, new processes began making them grow faster and altered their physical structure.

Growth of Protoplanets

- If planetesimals collided at orbital velocities, it is unlikely that they would have stuck together.
  - The average orbital velocity in the solar system is about 10 km/s (22,000 mph).
  - Head-on collisions at this velocity would have vaporized the material.

Growth of Protoplanets

- However, the planetesimals were all moving in the same direction in the nebular plane and didn’t collide head-on.
  - Instead, they merely rubbed shoulders at low relative velocities.
  - Such gentle collisions would have been more likely to fuse them than to shatter them.

Growth of Protoplanets

- The largest planetesimals would grow the fastest—they had the strongest gravitational field.
  - Also, they easily attract additional material.
  - Computer models indicate that these planetesimals grew quickly to protoplanetary dimensions, sweeping up more and more material.

Growth of Protoplanets

- Protoplanets had to begin growing by accumulating solid material.
  - This is because they did not have enough gravity to capture and hold large amounts of gas.

Growth of Protoplanets

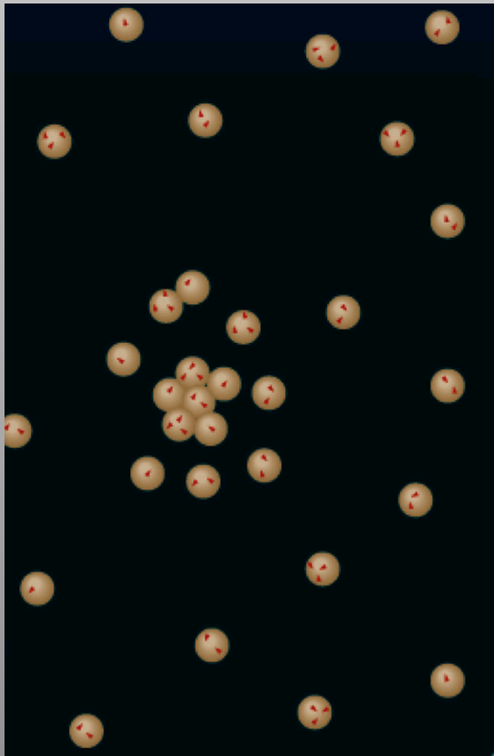
- In the warm solar nebula, the atoms and molecules of gas were traveling at velocities much larger than the escape velocities of modest-size protoplanets.
  - Thus, in their early development, the protoplanets could grow only by attracting solid bits of rock, metal, and ice.

Growth of Protoplanets

- Once a protoplanet approached a mass of 15 Earth masses or so, it could begin to grow by gravitational collapse.
  - This is the rapid accumulation of a large amount of infalling gas.

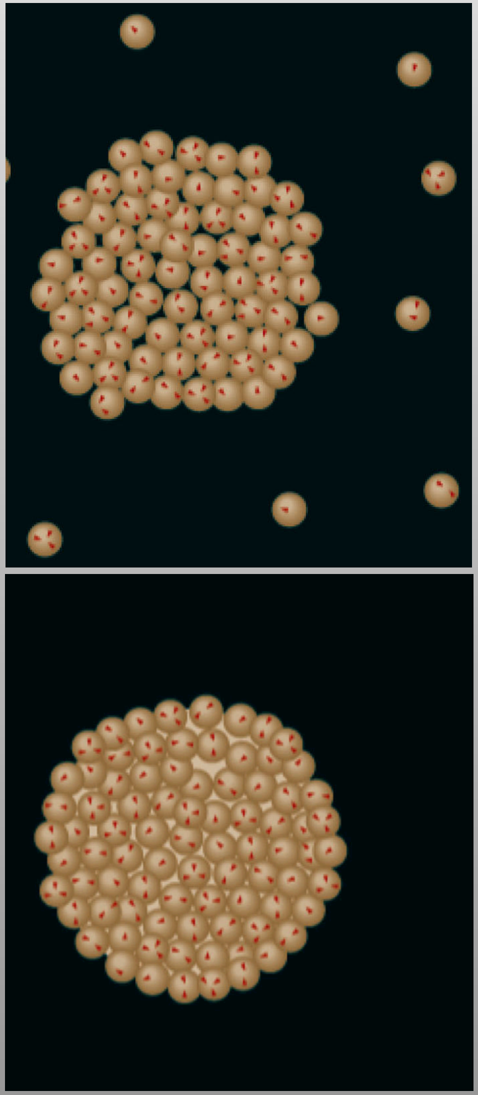
Growth of Protoplanets

- In its simplest form, the theory of terrestrial protoplanet growth supposes that all the planetesimals had about the same chemical composition.



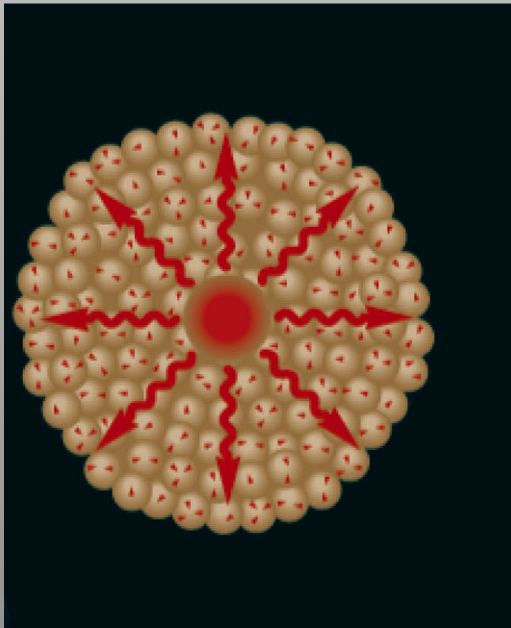
Growth of Protoplanets

- The planetesimals accumulated gradually to form a planet-size ball of material that was of homogeneous composition throughout.



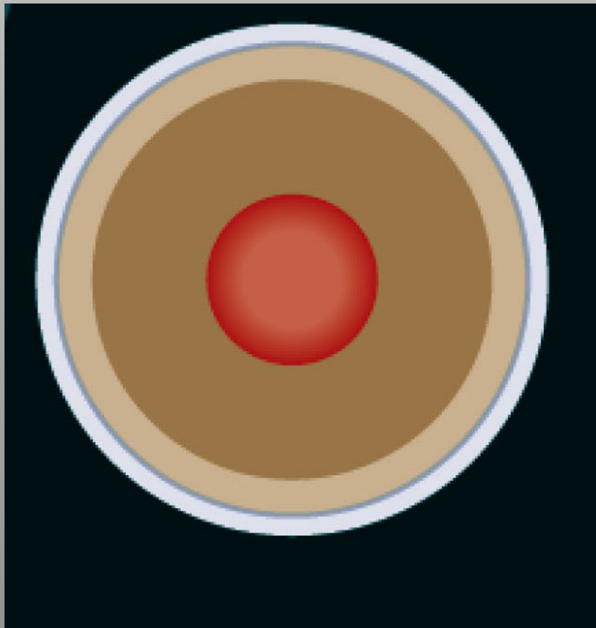
Growth of Protoplanets

- As a planet formed, heat began to accumulate in its interior from the decay of short-lived radioactive elements.
  - This heat eventually melted the planet and allowed it to differentiate.
  - Differentiation is the separation of material according to density.



Growth of Protoplanets

- When the planet melted, the heavy metals such as iron and nickel settled to the core.
- The lighter silicates floated to the surface to form a low-density crust.



Growth of Protoplanets

- This process depends on the presence of short-lived radioactive elements whose rapid decay would have released enough heat to melt the interior of planets.

Growth of Protoplanets

- Astronomers know such elements were present because very old rock from meteorites contains daughter isotopes such as magnesium-26.
  - That isotope is produced by the decay of aluminum-26 in a reaction that has a half-life of only 0.74 million years.

Growth of Protoplanets

- The aluminum-26 and similar short-lived radioactive isotopes are gone now.
- However, they must have been produced in a supernova explosion that occurred no more than a few million years before the formation of the solar nebula.

Growth of Protoplanets

- In fact, many astronomers suspect that this supernova explosion compressed nearby gas and triggered the formation of stars—one of which became the sun.
  - Thus, our solar system may exist because of a supernova explosion that occurred about 4.6 billion years ago.

Growth of Protoplanets

- If planets formed and were later melted by radioactive decay, gases released from the planet's interior would have formed an atmosphere.
- The creation of a planetary atmosphere from a planet's interior is called outgassing.

Growth of Protoplanets

- Models of the formation of Earth indicate that the local planetesimals would not have included much water.
  - So, some astronomers now think that Earth's water and some of its present atmosphere accumulated late in the formation of the planets.
  - Then, Earth swept up volatile-rich planetesimals forming in the cooling solar nebula.

Growth of Protoplanets

- Such icy planetesimals may have formed in the outer parts of the solar nebula.
  - They have been scattered by encounters with the Jovian planets in a bombardment of comets.

Growth of Protoplanets

- According to the solar nebula theory, the Jovian planets began growing by the same processes that built the terrestrial planets.
  - The outer solar nebula not only contained solid bits of metals and silicates—it also included abundant ices.
  - The Jovian planets grew rapidly and quickly became massive enough to grow by gravitational collapse—drawing in large amounts of gas from the solar nebula.

Growth of Protoplanets

- Ices could not condense as solids at the locations of the terrestrial planets.
  - So, those planets developed slowly and never became massive enough to grow by gravitational collapse.

Growth of Protoplanets

- The Jovian planets must have grown to their present size in about 10 million years.
  - Astronomers calculate that the sun then became hot and luminous enough to blow away the gas remaining in the solar nebula.

Growth of Protoplanets

- The terrestrial planets grew from solids and not from the gas.
  - So, they continued to grow by accretion from solid debris left behind when the gas was blown away.

Growth of Protoplanets

- Model calculations indicate the process of planet formation was almost completely finished by the time the solar system was 30 million years old.

Continuing Bombardment of the Planets

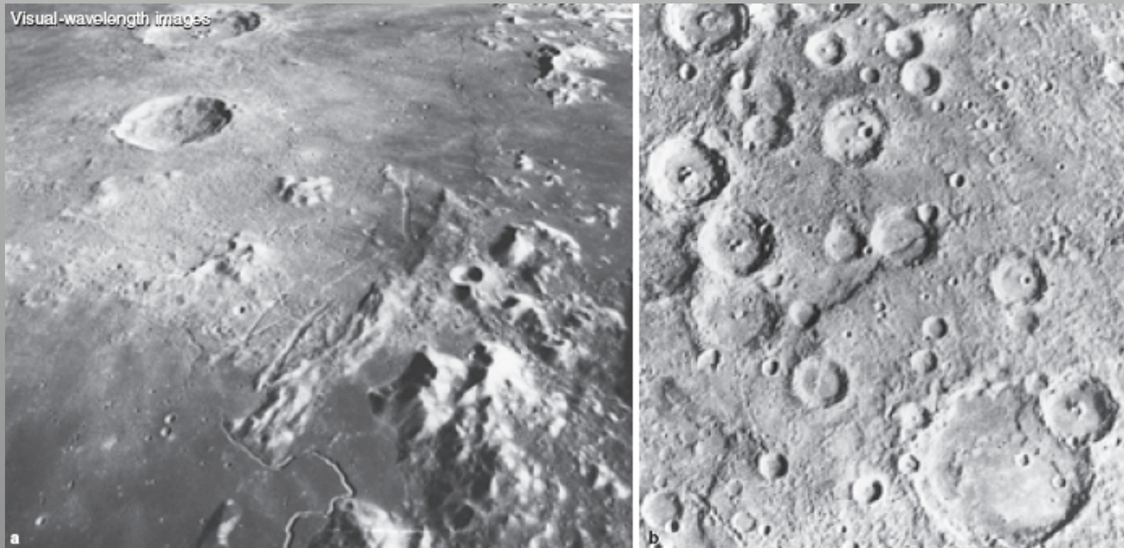
- Astronomers have good reason to believe that comets and asteroids can hit planets.

Continuing Bombardment of the Planets

- Meteorites hit Earth every day, and occasionally a large one can form a crater.
  - Earth is marked by about 150 known meteorite craters.

Continuing Bombardment of the Planets

- In a sense, this bombardment represents the slow continuation of the accretion of the planets.
  - Earth's moon, Mercury, Venus, Mars, and most of the moons in the solar system are covered with craters.



Continuing Bombardment of the Planets

- A few of these craters have been formed recently by the steady rain of meteorites that falls on all the planets in the solar system.

Continuing Bombardment of the Planets

- However, most of the craters you see appear to have been formed roughly 4 billion years ago as the last of the debris in the solar nebula was swept up by the planets.
  - This is called the heavy bombardment.

Continuing Bombardment of the Planets

- 65 million years ago, at the end of the Cretaceous period, over 75 percent of the species on Earth, including the dinosaurs, went extinct.

Continuing Bombardment of the Planets

- Scientists have found a thin layer of clay all over the world that was laid down at that time.
  - It is rich in the element iridium—common in meteorites, but rare in Earth's crust.
  - This suggests that a large impact altered Earth's climate and caused the worldwide extinction.

Continuing Bombardment of the Planets

- Mathematical models indicate that a major impact would eject huge amounts of pulverized rock high above the atmosphere.

Continuing Bombardment of the Planets

- As this material fell back, Earth's atmosphere would be turned into a glowing oven of red-hot meteorites streaming through the air.
  - This heat would trigger massive forest fires around the world.
  - Soot from such fires has been found in the final Cretaceous clay layers.

Continuing Bombardment of the Planets

- Once the firestorms are cooled, the remaining dust in the atmosphere would block sunlight and produce deep darkness for a year or more—killing off most plant life.

Continuing Bombardment of the Planets

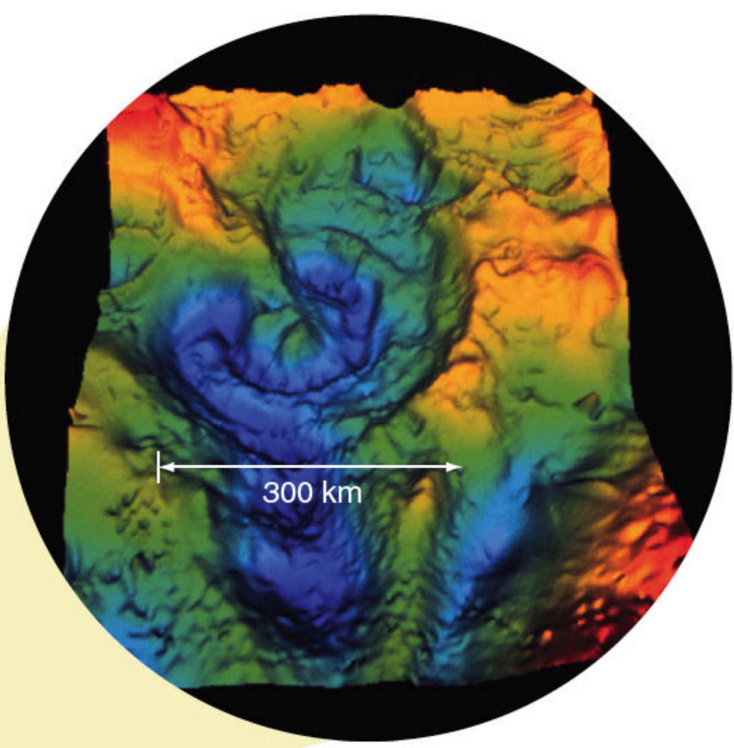
- Other effects, such as acid rain and enormous tsunamis (tidal waves), are also predicted by the models.

Continuing Bombardment of the Planets

- Geologists have located a crater at least 150 km in diameter centered near the village of Chicxulub in the northern Yucatán region of Mexico.

Continuing Bombardment of the Planets

- Although the crater is completely covered by sediments, mineral samples show that it contains shocked quartz typical of impact sites and that it is the right age.



Continuing Bombardment of the Planets

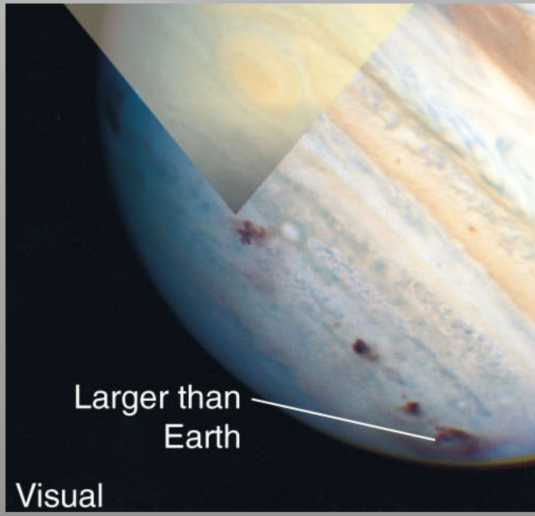
- The impact of an object 10 to 14 km in diameter formed the crater about 65 million years ago, just when the dinosaurs and many other species died out.
  - Most Earth scientists now believe that this is the scar of the impact that ended the Cretaceous period.

Continuing Bombardment of the Planets

- Earthlings watched in awe during six days in the summer of 1994 as 20 or more fragments from the head of comet Shoemaker-Levy 9 slammed into Jupiter.
  - This produced impacts equaling millions of megatons of TNT.

Continuing Bombardment of the Planets

- Each impact created a fireball of hot gases and left behind dark smudges that remained visible for months afterward.



Continuing Bombardment of the Planets

- Such impacts on Jupiter probably occur once every century or two.
- Major impacts on Earth occur less often because Earth is smaller, but they are inevitable.

Continuing Bombardment of the Planets

- We are sitting ducks.
  - All of human civilization is spread out over Earth's surface and exposed to anything that falls out of the sky.
  - Meteorites, asteroids, and comets bombard Earth, producing impacts that vary from dust settling on rooftops to blasts capable of destroying all life.

Continuing Bombardment of the Planets

- In this case, the scientific evidence is conclusive and highly unwelcome.
  - Statistically, you are quite safe.
  - The chance that a major impact will occur during your lifetime is so small that it is hard to estimate.

Continuing Bombardment of the Planets

- However, the consequences of such an impact are so severe that humanity should be preparing.
  - One way to prepare is to find those NEOs (Near Earth Objects) that could hit this planet, map their orbits in detail, and identify any that are dangerous.

The Jovian Problem

- The solar nebula theory has been very successful in explaining the formation of the solar system.
- However, there are some problems.
  - The Jovian planets are the troublemakers.
  - The gas and dust disks around newborn stars don’t
    last long.

The Jovian Problem

- Earlier, you saw images of dusty gas disks around the young stars in the Orion nebula.
  - Those disks are being evaporated by the intense ultraviolet radiation from hot stars within the nebula.

The Jovian Problem

- Astronomers estimate that most stars form in clusters containing some massive stars.
  - So, this evaporation process must happen to most disks.

The Jovian Problem

- Even if a disk did not evaporate quickly, model calculations predict that the gravitational influence of the crowded stars in a cluster should quickly strip away the outer parts of the disk.

The Jovian Problem

- This is a troublesome observation.
  - It seems to mean that planet-forming disks around young stars are unlikely to last longer than a few million years, and many must evaporate within 100,000 years or so.
  - That's not long enough to grow a Jovian planet by the processes in the solar nebula theory.
  - Yet, Jovian planets are common in the universe.

The Jovian Problem

- A modification to the solar nebula theory has come from mathematical models of the solar nebula.

The Jovian Problem

- The results show that the rotating gas and dust of the solar nebula may have become unstable and formed outer planets by direct gravitational collapse.
  - That is, massive planets may have been able to form from the gas without first forming a dense core by accretion.
  - Jupiters and Saturns form in these calculated models within a few hundred years.

The Jovian Problem

- If the Jovian planets formed in this way, they could have formed quickly—before the solar nebula disappeared.

The Jovian Problem

- This new insight into the formation of the outer planets may help explain the formation of Uranus and Neptune.
  - They are so far from the sun that accretion could not have built them rapidly.
  - It is hard to understand how they could have reached their present mass in a region where the material should have been sparse and orbital speeds are slow.

The Jovian Problem

- Theoretical calculations show that Uranus and Neptune might instead have formed closer to the sun, in the region of Jupiter and Saturn.
  - They then moved outward by gravitational interactions with the other planets or with planetesimals in the Kuiper belt.
  - In any case, the formation of Uranus and Neptune is part of the Jovian problem.

The Jovian Problem

- The traditional solar nebula theory proposes that the planets formed by accreting a core and then, if they became massive enough, by gravitational collapse of nebula gas.
- The new theories suggest that some of the outer planets could have skipped the core accretion phase.

Explaining the Characteristics of the Solar System

- Now, you have learned enough to put all the pieces of the puzzle together and explain the distinguishing characteristics of the solar system in the table.

Table 12.1 Characteristic Properties of the Solar System

1.	Disk shape of the solar system Orbits in nearly the same plane Common direction of revolution and rotation
2.	Two planetary types Terrestrial—inner planets; small, high density Jovian—outer planets; large, low density
3.	Planetary rings and large satellite systems around the Jovian planets, not around the Terrestrial planets
4.	Space debris—asteroids, comets, and meteors Composition: two types, rocky versus icy Orbits: two types, inner versus outer solar system
5.	Common age of about 4.6 billion years for Earth, the moon, Mars, meteorites, and the sun

Explaining the Characteristics of the Solar System

- The disk shape of the solar system is inherited from the solar nebula.
- The sun and planets revolve and rotate in the same direction because they formed from the same rotating gas cloud.

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Explaining the Characteristics of the Solar System

- The orbits of the planets lie in the same plane because the rotating solar nebula collapsed into a disk, and the planets formed in that disk.

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Explaining the Characteristics of the Solar System

- The solar nebula hypothesis calls on continuing evolutionary processes to gradually build the planets.
- Scientists call this type of explanation an evolutionary theory.

Explaining the Characteristics of the Solar System

- In contrast, a catastrophic theory invokes special, sudden, even violent, events.

Explaining the Characteristics of the Solar System

- Uranus rotates on its side.
- Venus rotates backward.
  - Both these peculiarities could have been caused by off-center impacts of massive planetesimals they were forming.
  - This is an explanation of the catastrophic type.

Explaining the Characteristics of the Solar System

- On the other hand, computer models suggest that the sun can produce tides in the thick atmosphere of Venus and eventually reverse the planet's rotation.
  - an explanation of the evolutionary type

Explaining the Characteristics of the Solar System

- The division of the planets into terrestrial and Jovian worlds can be understood through the condensation sequence.

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Explaining the Characteristics of the Solar System

- The terrestrial planets formed in the inner part of the solar nebula.
  - Here, the temperature was high.
  - Only compounds such as the metals and silicates could condense to form solid particles.
  - That produced the small, dense terrestrial planets.

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Explaining the Characteristics of the Solar System

- In contrast, the Jovian planets formed in the outer solar nebula.
  - Here, the lower temperature allowed the gas to form large amounts of ices—perhaps three times more ices than silicates.
  - This allowed the planets to grow rapidly and become massive low-density worlds.

Table 12.2 The Condensation Sequence

Temperature (K)	Condensate	Object (Estimated Temperature of Formation; K)
1,500	Metal oxides	Mercury (1,400)
1,300	Metallic iron and nickel	
1,200	Silicates	
1,000	Feldspars	Venus (900)
680	Troilite (FeS)	Earth (600) Mars (450)
175	H_2O ice	Jovian (175)
150	Ammonia–water ice	
120	Methane–water ice	
65	Argon–neon ice	Pluto (65)

Explaining the Characteristics of the Solar System

- Also, Jupiter and Saturn are so massive they have been able to grow even larger by drawing in the cool gas directly from the solar nebula.
- The terrestrial planets could not do this because they never became massive enough.

Explaining the Characteristics of the Solar System

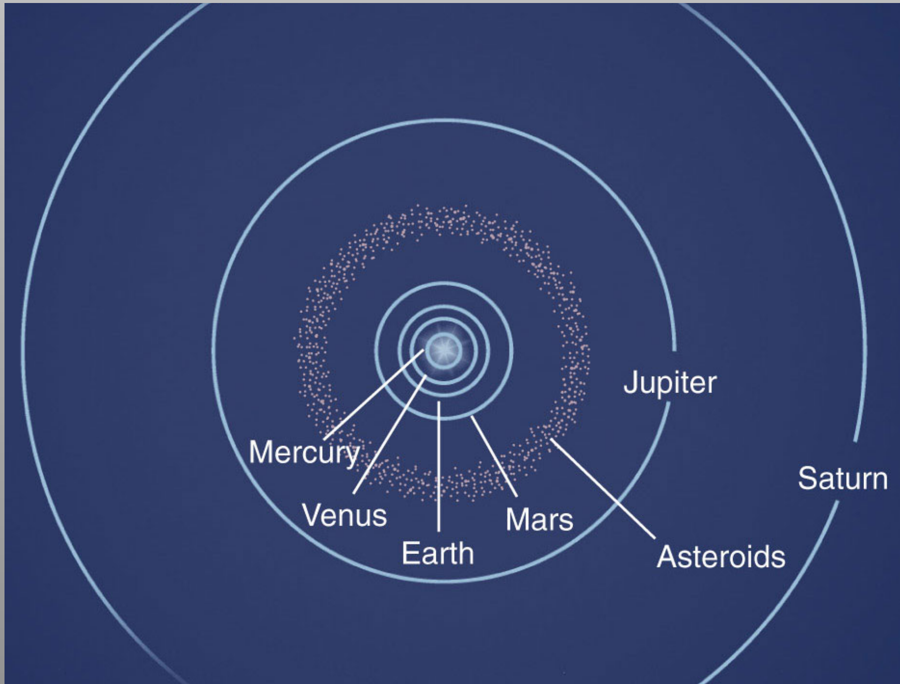
- The heat of formation—the energy released by infalling matter—was tremendous for these massive planets.
  - Jupiter must have grown hot enough to glow with a luminosity of about 1 percent that of the present sun.
  - However, because it never got hot enough to start nuclear fusion as a star would, it never generated its own energy.

Explaining the Characteristics of the Solar System

- Jupiter is still hot inside.
- In fact, both Jupiter and Saturn radiate more heat than they absorb from the sun.
  - So, they are evidently still cooling.

Explaining the Characteristics of the Solar System

- A glance at the solar system suggests that you should expect to find a planet between Mars and Jupiter at the present location of the asteroid belt.



Explaining the Characteristics of the Solar System

- Mathematical models show that Jupiter grew into a massive planet.
- It was able to gravitationally disturb the motion of nearby planetesimals.

Explaining the Characteristics of the Solar System

- The bodies that should have formed a planet between Mars and Jupiter were broken up, thrown into the sun, or ejected from the solar system.
  - This was due to the gravitational influence of massive Jupiter.
  - The asteroids seen today are the last remains of those rocky planetesimals.

Explaining the Characteristics of the Solar System

- In contrast, the comets are evidently the last of the icy planetesimals.
  - Some may have formed in the outer solar nebula beyond Neptune and Pluto.
  - However, many probably formed among the Jovian planets—where ices could condense easily.

Explaining the Characteristics of the Solar System

- Mathematical models show that the massive Jovian planets could have ejected some of these icy planetesimals into the far outer solar system.
- This region is called the Oort cloud.
  - Comets come from here with very long periods and orbits highly inclined to the plane of the solar system.

Explaining the Characteristics of the Solar System

- The icy Kuiper belt objects, including Pluto, appear to be ancient planetesimals.
  - They formed in the outer solar system but were never incorporated into a planet.
  - They orbit slowly far from the light and warmth of the sun.
  - Except for occasional collisions, they have not changed much since the solar system was young.

Explaining the Characteristics of the Solar System

- All four Jovian worlds have ring systems.
  - You can understand this by considering the large mass of these worlds and their remote location in the solar system.

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Explaining the Characteristics of the Solar System

- A large mass makes it easier for a planet to hold onto orbiting ring particles.
- Also, being farther from the sun, the ring particles are not as easily swept away by the pressure of sunlight and the solar wind.
  - It is hardly surprising, then, that the terrestrial planets —low-mass worlds located near the sun—have no planetary rings.

Explaining the Characteristics of the Solar System

- The solar nebula theory has no difficulty explaining the common ages of solar system bodies.
  - If the hypothesis is correct, then the planets formed at the same time as the sun.
  - Thus, they should have roughly the same age.

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Planets Orbiting Other Stars

- Are there planets orbiting other stars?
- Are there planets like Earth?
  - The evidence so far makes that seem likely.

Planet-Forming Disks Around Other Suns

- You have already learned about dense disks of gas and dust around stars that are forming.
  - For example, at least 50 percent of the stars in the Orion nebula are encircled by dense disks of gas and dust.
  - They have more than enough mass to make planetary systems like ours.

Planet-Forming Disks Around Other Suns

- The Orion star-forming region is only a few million years old.
  - So, it does not seem likely that planets have finished forming in these disks yet.

Planet-Forming Disks Around Other Suns

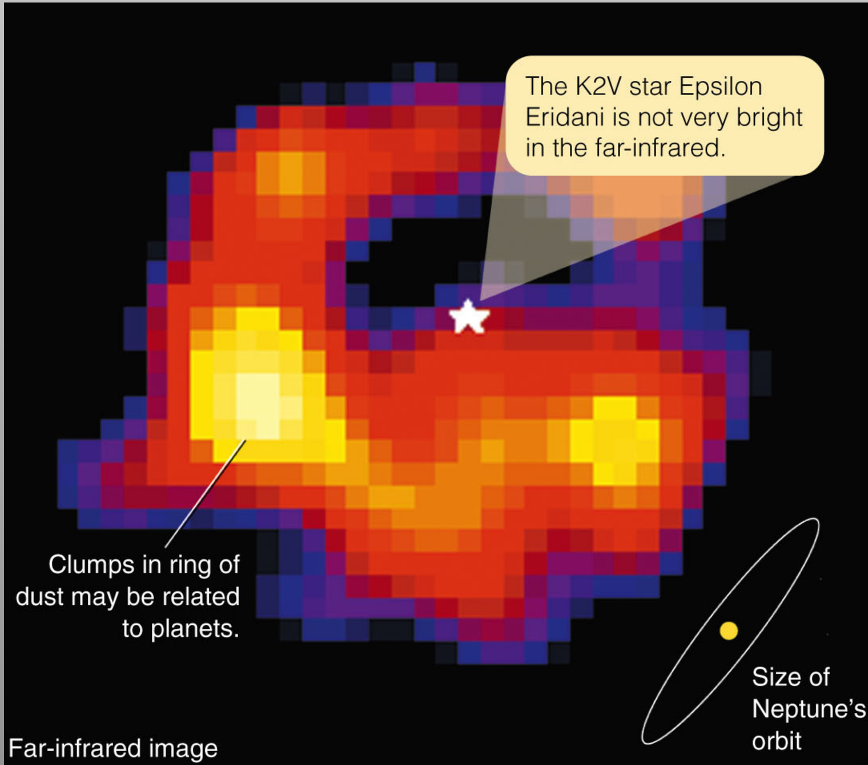
- Nevertheless, the important point for astronomers is:
  - Disks of gas and dust that could become planetary systems are a common feature of star formation.

Debris Disks

- Also, infrared astronomers have found very cold, low-density dust disks around older stars such as Vega and Beta Pictoris.
  - Although much younger than the sun, these stars are on the main sequence and have completed their formation.
  - So, they are clearly in a later stage than the newborn stars in Orion.

Debris Disks

- These low-density disks generally have innermost zones with even lower-density places where planets may have formed.



Debris Disks

- Such tenuous dust disks are sometimes called debris disks.
  - This is because they are understood to be dusty debris released in collisions among small bodies such as comets, asteroids, and Kuiper belt objects.

Debris Disks

- Our own solar system is known to contain such dust.
  - Astronomers believe the sun has an extensive debris disk of cold dust extending far beyond the orbits of the planets.

Debris Disks

- Few planets orbiting stars with debris disks have been detected so far.
  - However, the presence of dust particles with lifetimes shorter than the ages of the stars assures you that remnant planetesimals like asteroids and comets are present as the sources of the dust.

Debris Disks

- If planetesimals are there, then you can expect that there are also planets orbiting those stars.
  - Many of the debris disks have details of structure and shape that are probably caused by the gravity of planets orbiting within or at the edges of the debris.

Debris Disks

- Notice the difference between the two kinds of disks that astronomers have found.
  - The low-density dust disks such as the one around Beta Pictoris are produced by dust from collisions among comets, asteroids, and Kuiper belt objects.
  - Such disks are evidence that planetary systems have already formed.
  - The dense disks of gas and dust such as those seen around the stars in Orion are sites where planets could be forming right now.

Extrasolar Planets

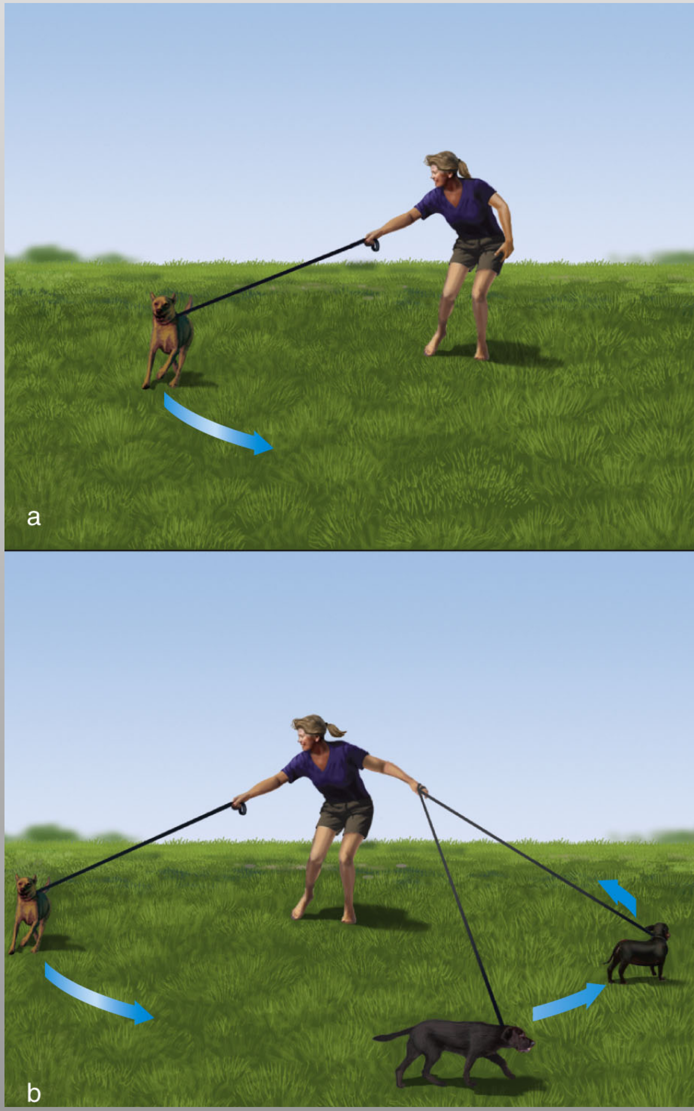
- A planet orbiting another star is called an extrasolar planet.
  - Such a planet would be quite faint and difficult to detect so close to the glare of its star.
  - However, there are ways to find these planets.
  - To see how, all you have to do is imagine walking a dog.

Extrasolar Planets

- You will remember that Earth and its moon orbit around their common center of mass.
- When a planet orbits a star, the star moves very slightly as it orbits the center of mass of the planet-star system.

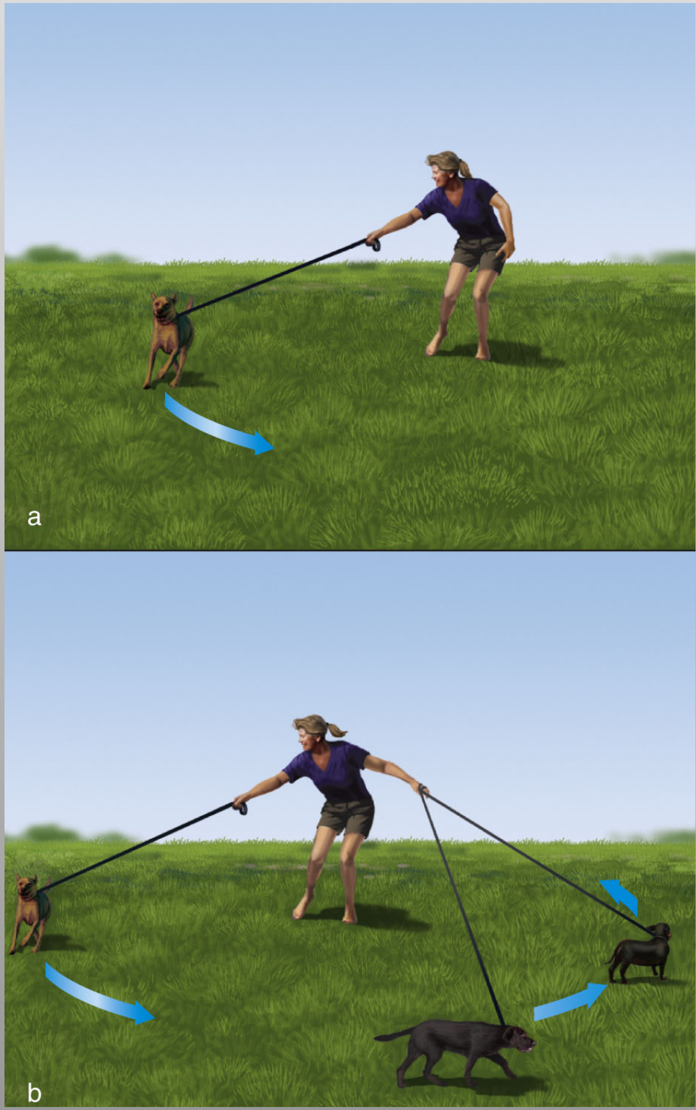
Extrasolar Planets

- Think of someone walking a poorly trained dog on a leash.
  - The dog runs around pulling on the leash.
  - Even if it were an invisible dog, you could plot its path by watching how its owner was jerked back and forth.



Extrasolar Planets

- In the same way, astronomers can detect a planet orbiting another star—by watching how the star moves as the planet tugs on it.

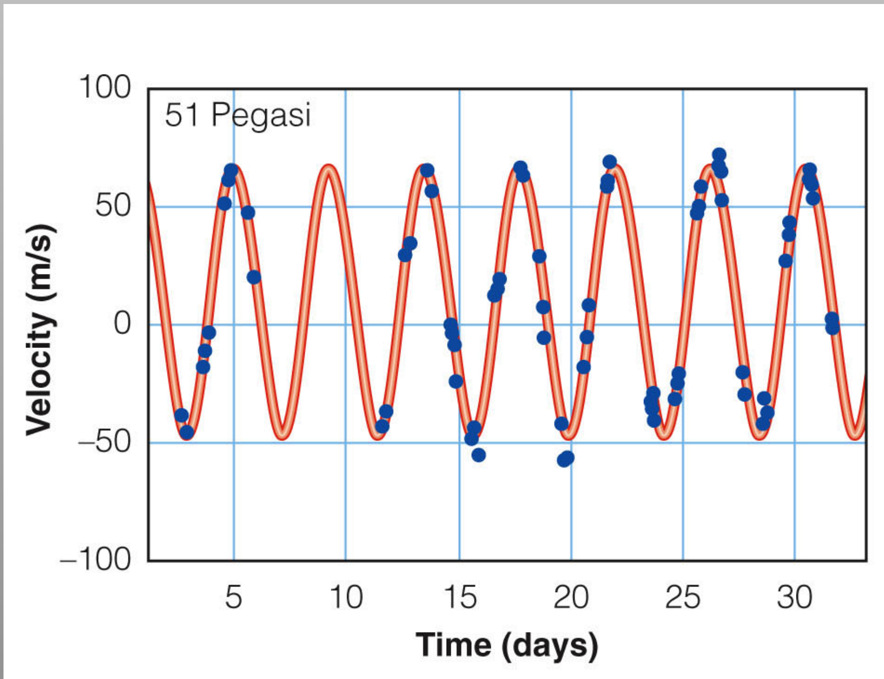


Extrasolar Planets

- The first planet detected this way was discovered in 1995.
  - It orbits the star 51 Pegasi.
  - As the planet circles the star, the star wobbles slightly.

Extrasolar Planets

- The very small motions of the star are detectable as Doppler shifts in the star’s spectrum.
  - This is the same technique used to study spectroscopic binary stars.



Extrasolar Planets

- From the motion of the star and estimates of the star's mass, astronomers can deduce that the planet has half the mass of Jupiter and orbits only 0.05 AU from the star.
  - Half the mass of Jupiter amounts to 160 Earth masses.
  - This is a large planet, larger than Saturn.

Extrasolar Planets

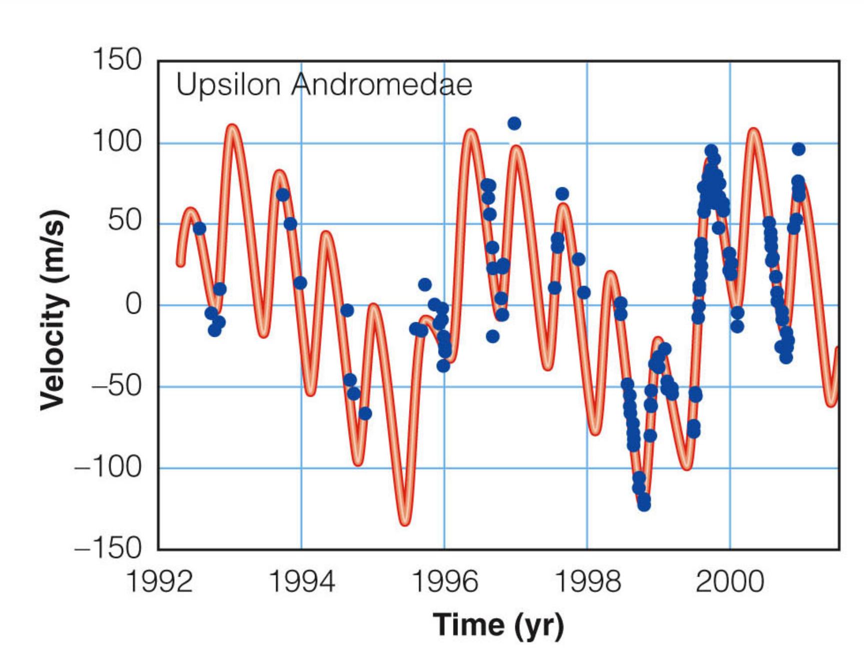
- Astronomers were not surprised by the announcement that a planet orbits 51 Pegasi.
  - For years, they had assumed that many stars had planets.

Extrasolar Planets

- Nevertheless, they greeted the discovery with typical skepticism.
  - That skepticism led to careful tests of the data and further observations that confirmed the discovery.

Extrasolar Planets

- Over 400 planets have been discovered in this way—including at least three planets orbiting the star Upsilon Andromedae, and five orbiting 55 Cancri—true planetary system.
  - More than 40 such multiple-planet systems have been found.



Extrasolar Planets

- Another way to search for planets is to look for changes in the brightness of a star when the orbiting planet crosses in front of or behind it.
  - The decrease in light is very small—but it is detectable.

Extrasolar Planets

- Astronomers have used this technique to detect a few planets as they crossed in front of their stars.
  - From the amount of light lost, astronomers can tell that these planets are roughly the size of Jupiter.

Extrasolar Planets

- The Spitzer Infrared Space Telescope has detected two planets when they passed behind their stars.
  - These planets are hot and emit significant infrared radiation.
  - As they orbit their parent stars, astronomers detect variation in the amount of infrared from the system.
  - This further confirms the existence of extrasolar planets and indicates the temperatures and sizes of the planets.

Extrasolar Planets

- Measurements of these and other planets that pass in front of and behind their stars reveal that they have Jupiter-like diameters as well as masses.
  - So, astronomers conclude they have Jovian densities and compositions.

Extrasolar Planets

- The planets discovered so far tend to be massive and have short periods.
- This is because lower-mass planets or longer-period planets are harder to detect.
  - Low-mass planets don't tug on their stars very much.
  - Present-day spectrographs can't detect the very small velocity changes that these gentle tugs produce.

Extrasolar Planets

- Planets with longer periods are harder to detect because Earth's astronomers have not been making high-precision observations for a long enough time yet.
  - Jupiter takes 11 years to circle the sun once.
  - So, it will take years for astronomers to see the longer-period wobbles produced by planets lying farther from their stars.

Extrasolar Planets

- You should not be surprised that the first extrasolar planets discovered are massive and have short periods.
    - This is called a selection effect.

Extrasolar Planets

- The new planets may seem odd for another reason.
  - In our own solar system, the large planets formed farther from the sun where the solar nebula was colder and ices could condense.

Extrasolar Planets

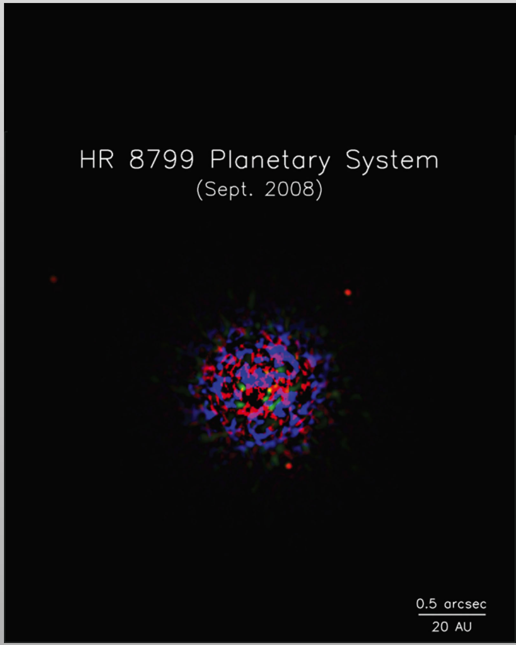
- How could big planets form so near their stars?
  - Model calculations predict that planets that form in an especially dense disk of matter could spiral inward as they sweep up gas or planetesimals.
  - That means it is possible for a few planets to become the massive, short-period planets that are detected most easily.

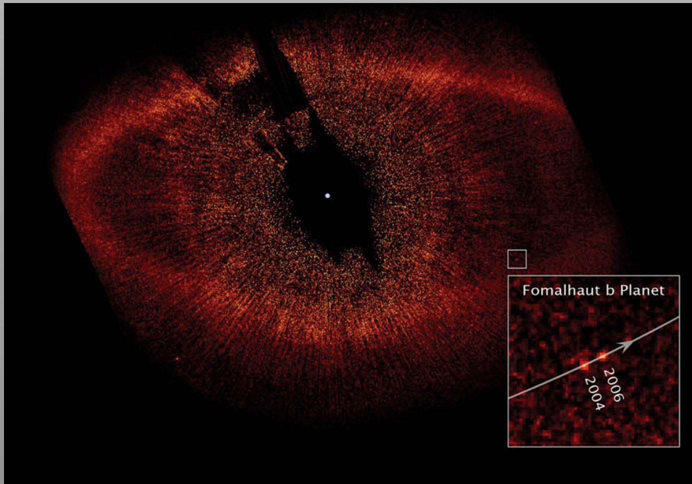
Extrasolar Planets

- Actually getting an image of a planet orbiting another star is about as easy as photographing a bug crawling on the bulb of a searchlight miles away.
- Planets are small and dim and get lost in the glare of the stars they orbit.

Extrasolar Planets

- Nevertheless, during 2008 astronomers managed to image planets around two A-type stars using Gemini and Keck telescopes on the ground and the Hubble Space Telescope.





Extrasolar Planets

- The discovery of extrasolar planets gives astronomers added confidence in the solar nebula theory.
  - The theory predicts that planets are common.
  - Astronomers are finding them orbiting many stars.