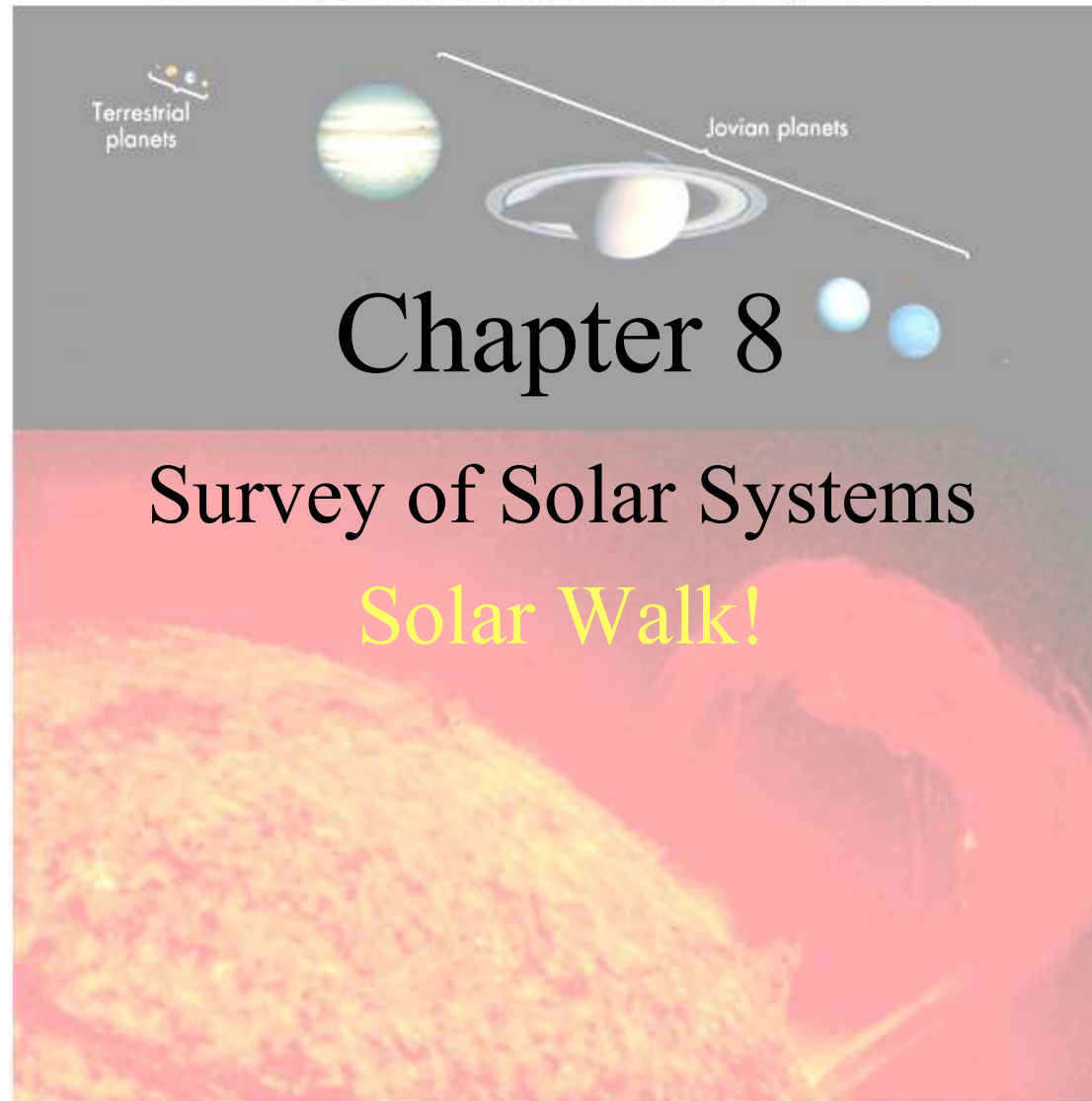


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The Solar System



- The *Solar System* is occupied by a diversity of objects, but shows an underlying order in the dynamics of their movements
- The planets form two main families:
 - solid rocky inner planets
 - gaseous/liquid outer planets
- Astronomers deduce that the Solar System formed some **4.5 billion years ago** out of the collapse of a huge cloud of gas and dust

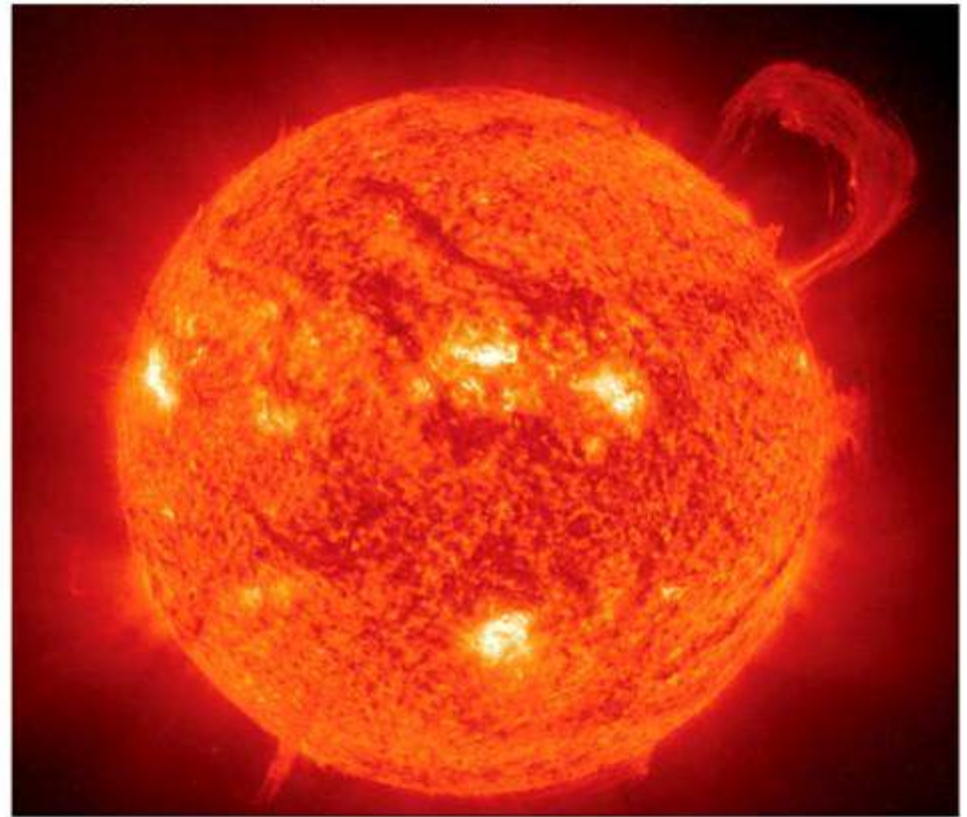
The Sun



- The Sun is a star, a ball of incandescent gas whose output is generated by nuclear reactions in its core
- Composed mainly of **hydrogen (71%) and helium (27%)**, it also contains traces of nearly all the other chemical elements

The Sun

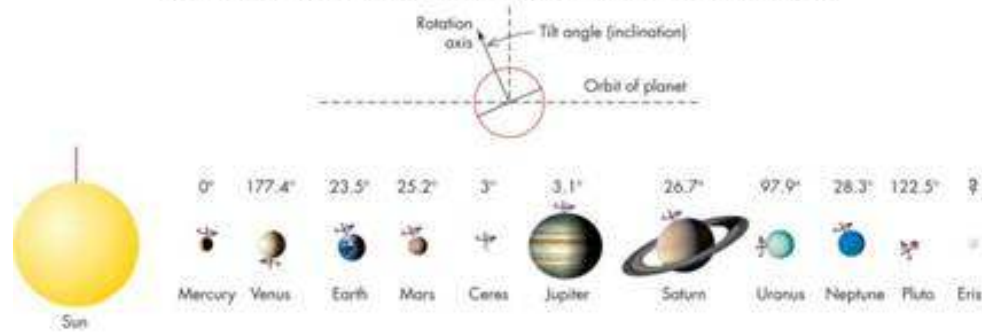
- It is the most massive object in the Solar System – 700 times the mass of the rest of the Solar System combined



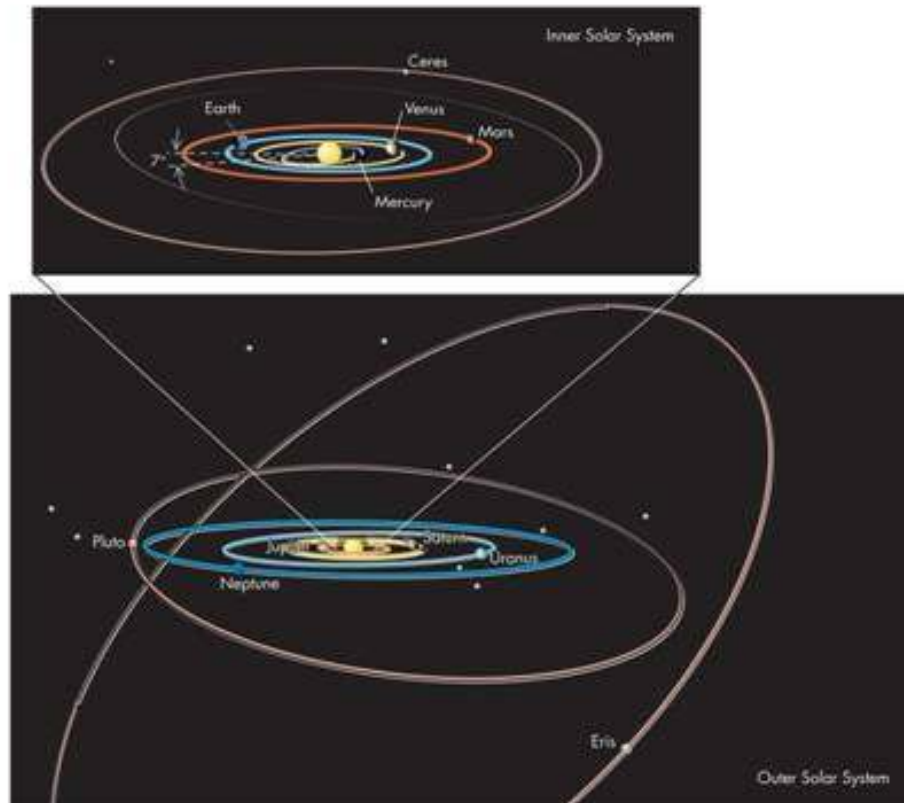
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- Its large mass provides the gravitational force to hold all the Solar System bodies in their orbital patterns around the Sun

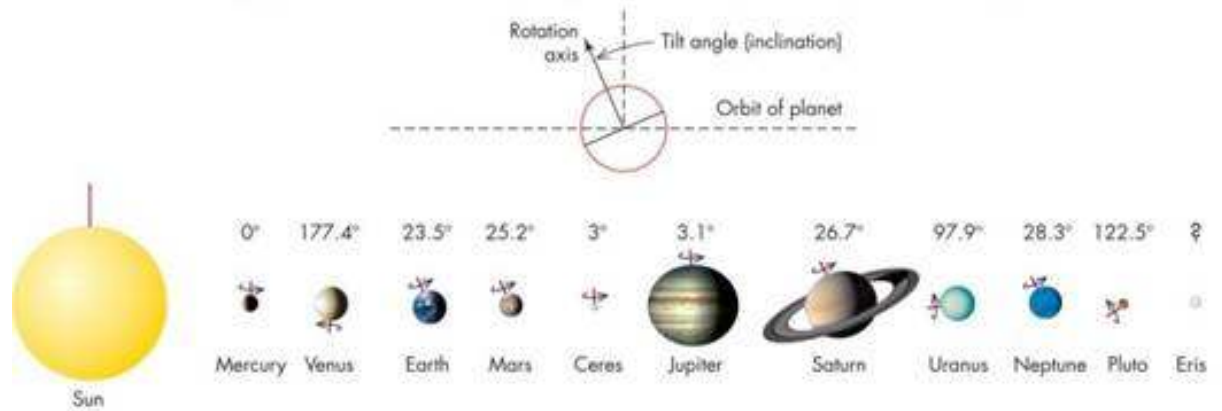
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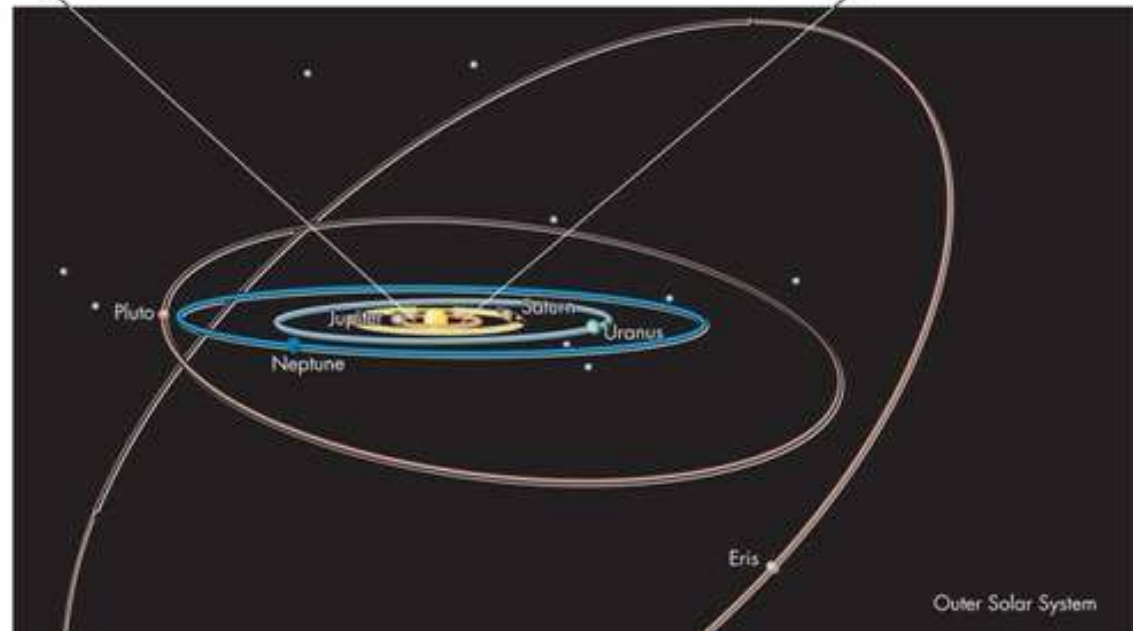
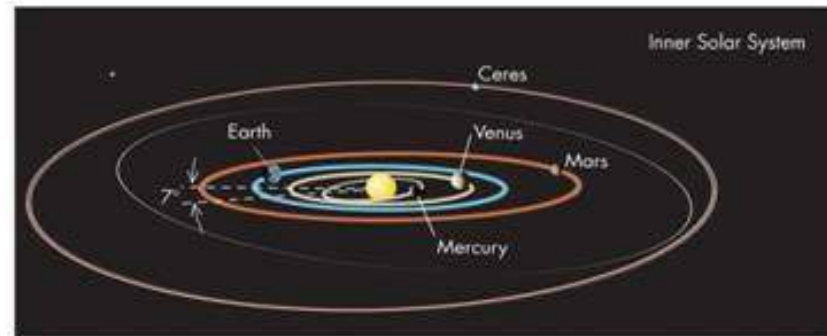
The Planets



- Orbits are almost **circular** lying in nearly the same plane. Pluto (not a planet) is the exception with a high (17°) inclination of its orbit.



The Planets

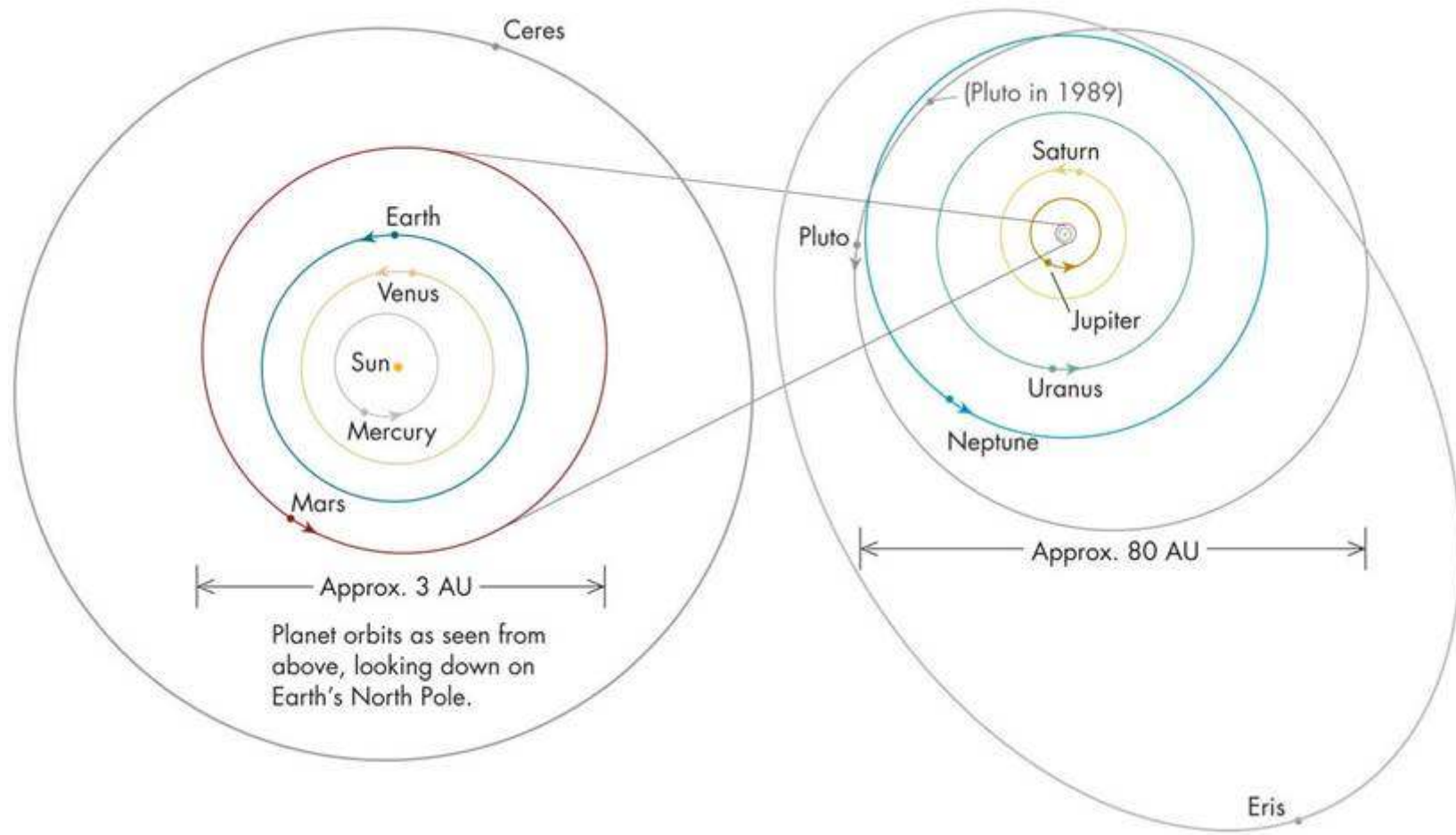


The Planets

- All of the planets travel counterclockwise around the Sun (as seen from high above the Earth's north pole)
- Six planets rotate counterclockwise; Venus rotates clockwise (retrograde rotation), and Uranus appears to rotate on its side

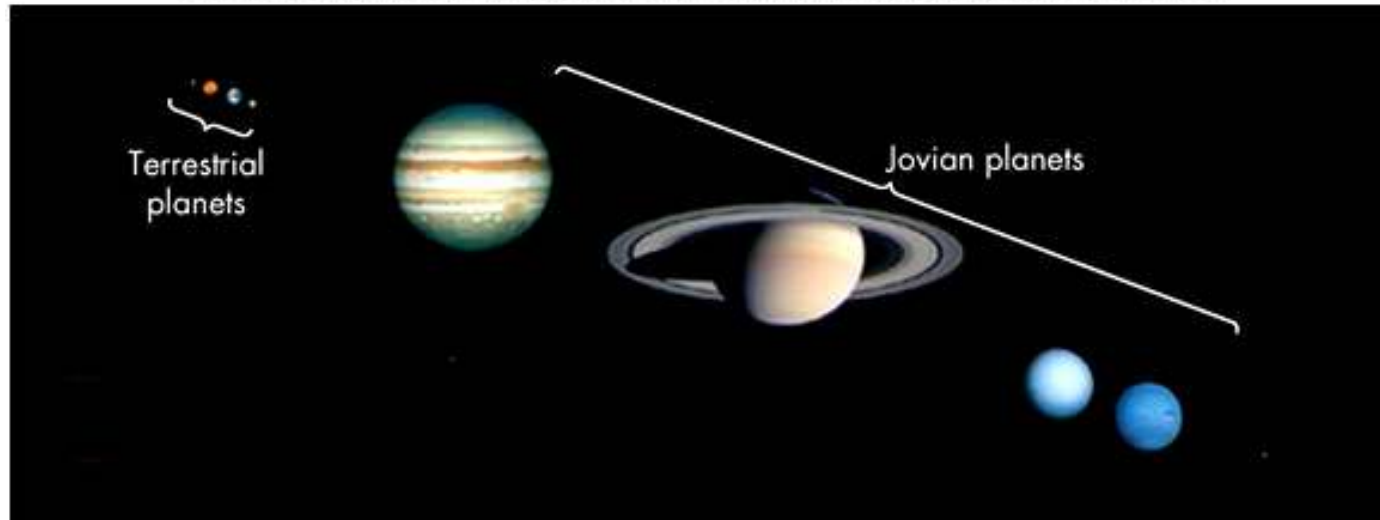
The Planets

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Inner Planets

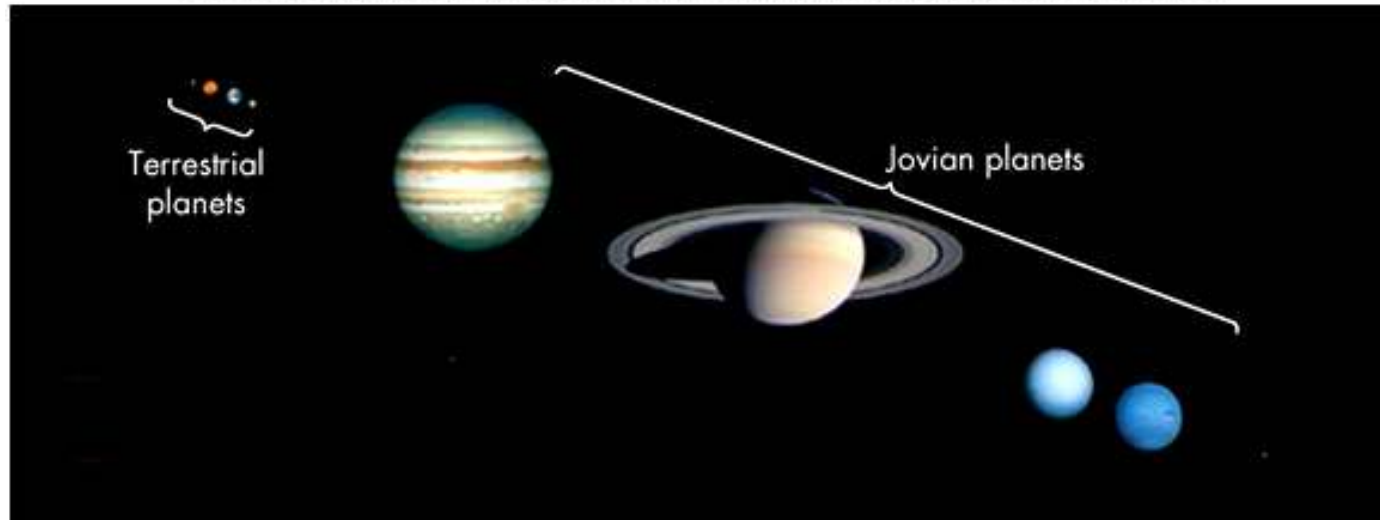
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- Mercury, Venus, Earth, Mars
- Small rocky (mainly silicon and oxygen) bodies with relatively thin or no atmospheres
- Also known as *terrestrial planets*

Outer Planets

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- Jupiter, Saturn, Uranus, and Neptune
- Gaseous, liquid, or icy (H_2O , CO_2 , CH_4 , NH_3)
- Also referred to as *Jovian planets*
- Jovian planets are much larger than terrestrial planets and do not have a well-defined surface

Dwarf Planets

- Pluto and similar objects fail to fit into either family
- Recently, scientists have discovered more than 200 similar objects orbiting the Sun at the same distance as Pluto
- In 2006, a new family was introduced – the dwarf planets
 - Massive enough to pull themselves spherical
 - Orbits have not been swept clear of debris

Satellites

- The number of planetary satellites changes frequently as more are discovered!
 - Jupiter 63
 - Saturn 60
 - Uranus 27
 - Neptune 13
 - Mars 2
 - Earth 1
 - Mercury and Venus are moonless
 - Even Pluto and Eris have moons!

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Dione



Enceladus



Titania

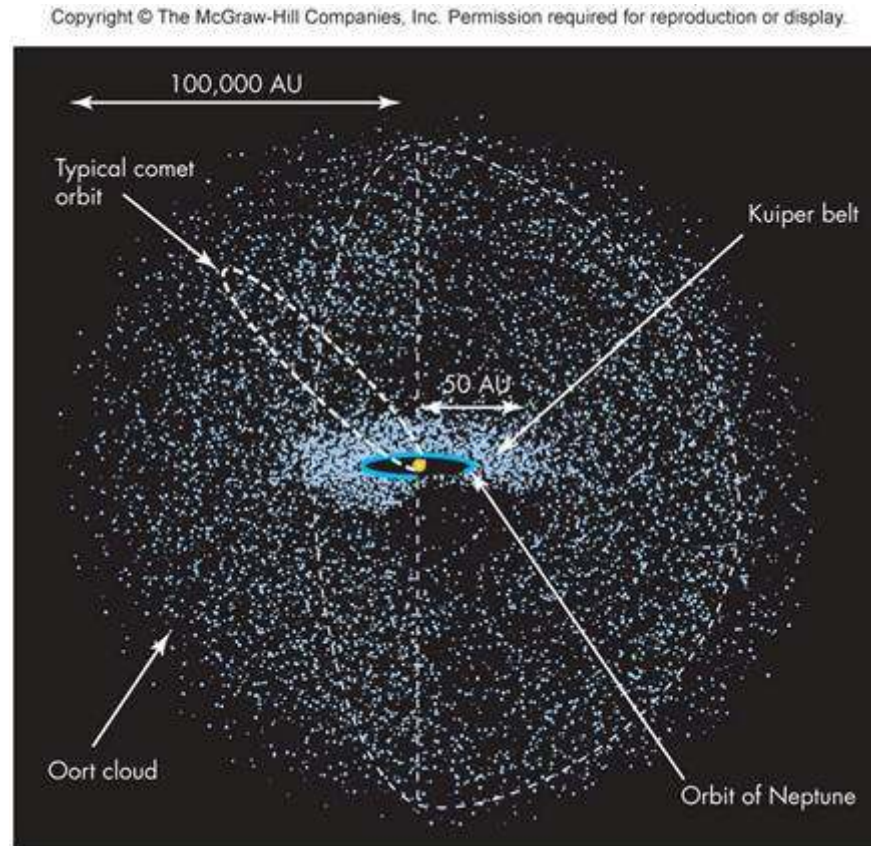
Asteroids and Comets

- Composition and size
 - *Asteroids* are rocky or metallic bodies ranging in size from a few **meters to 1000 km across** (about 1/10 the Earth's diameter)
 - *Comets* are **icy** bodies about 10 km or less across that can grow very long tails of gas and dust as they near the Sun and are vaporized by its heat

Asteroids and Comets

- Their location within Solar System
 - Most asteroids are in the *asteroid belt* between Mars and Jupiter indicating that these asteroids are the failed building-blocks of a planet
 - Some comets may also come from a disk-like swarm of icy objects that lies beyond Neptune and extends to perhaps 1000 AU, a region called the *Kuiper Belt*

Asteroids and Comets



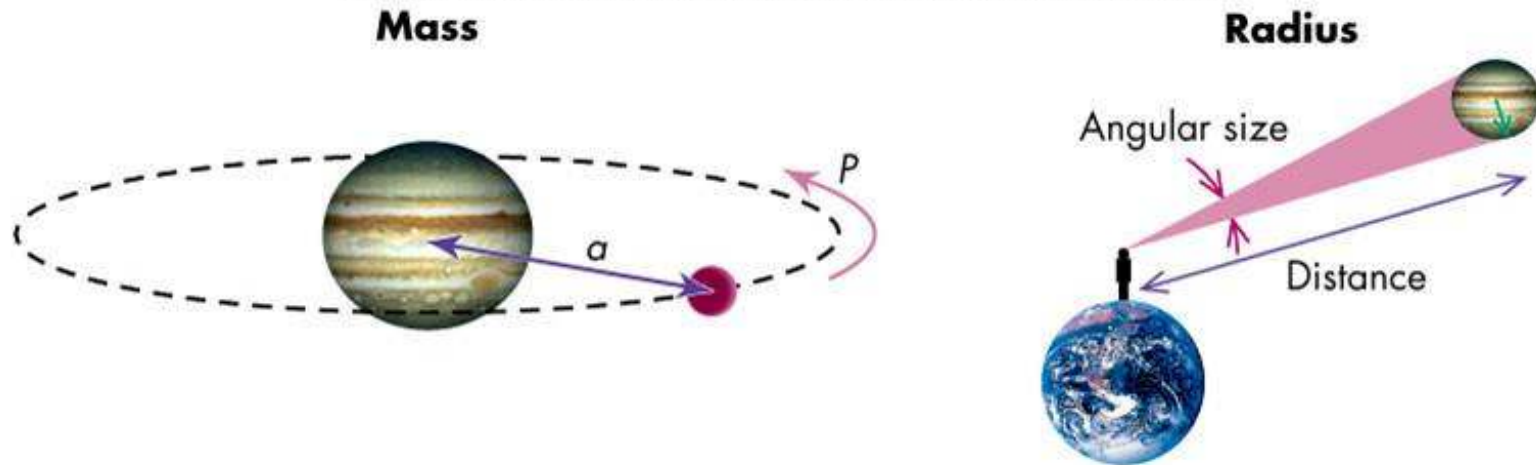
Most comets orbit the Sun far beyond Pluto in the ***Oort cloud***, a spherical shell extending from **40,000 to 100,000 AU** from the Sun

Measuring Composition

- Since the inner and outer planets differ dramatically in composition, it is important to understand how composition is determined
- A planet's **reflection spectrum (albedo)** can reveal a planet's atmospheric contents and the nature of surface rocks
- Seismic activity has only been measured on Earth for the purposes of determining interior composition

Measuring Composition: Density

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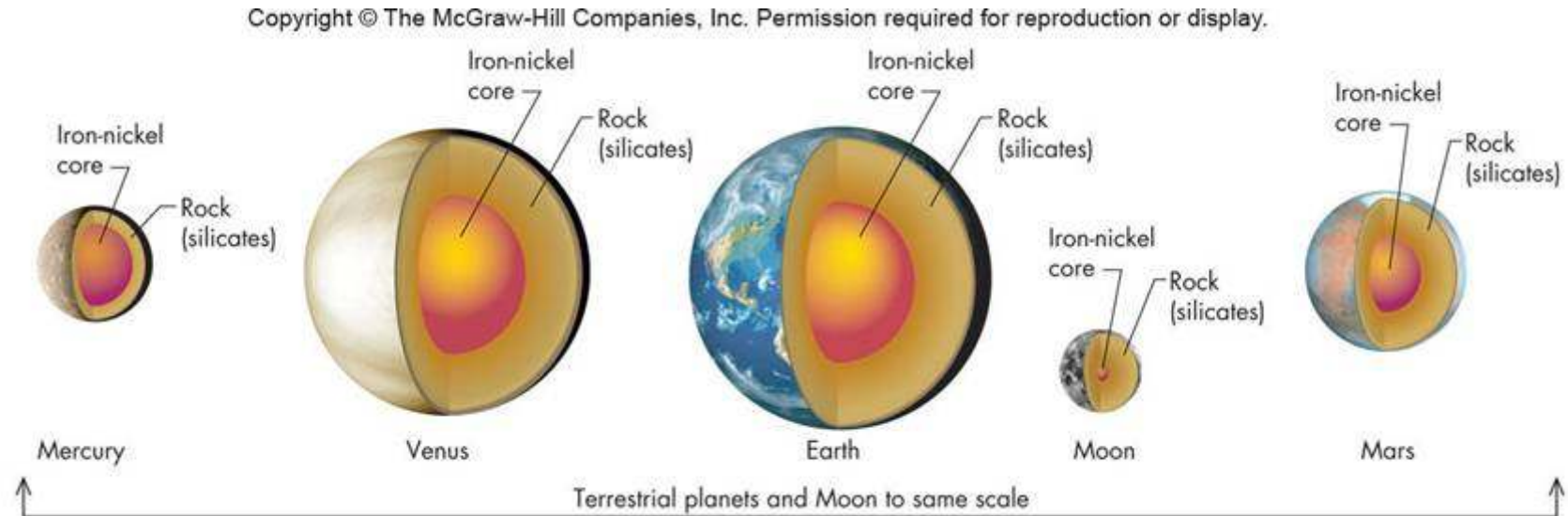


- A planet's average density is determined by dividing a planet's mass by its volume
 - Mass determined from Kepler's modified third law
 - Volume derived from a planet's measured radius

Measuring Composition: Density

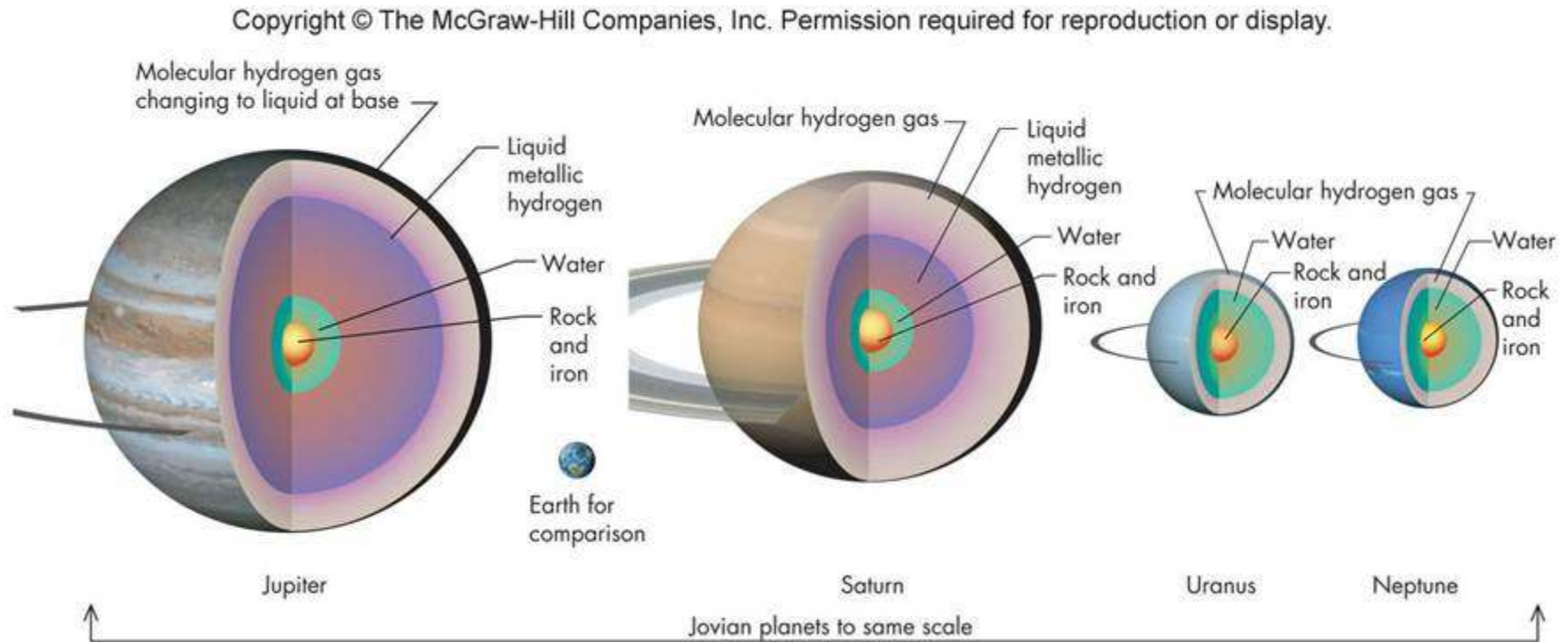
- Once average density known, the following factors are taken into account to determine a planet's interior composition and structure:
 - Densities of abundant, candidate materials
 - Variation of these densities as a result of compression due to gravity
 - Surface composition determined from reflection spectra
 - Material separation by density differentiation
 - Mathematical analysis of equatorial bulges

Analysis Concludes:



- The **terrestrial planets**, with average densities ranging from **3.9 to 5.5 g/cm³**, are largely rock and iron, have iron cores, and have relative element ratios similar to the Sun except for deficiencies in lightweight gasses

Analysis Concludes:



- The **Jovian planets**, with average densities ranging from **0.71 to 1.67 g/cm³**, have relative element ratios similar to the Sun and have Earth-sized rocky cores.
- Yep! Saturn would float on water!!!!

Age of the Solar System

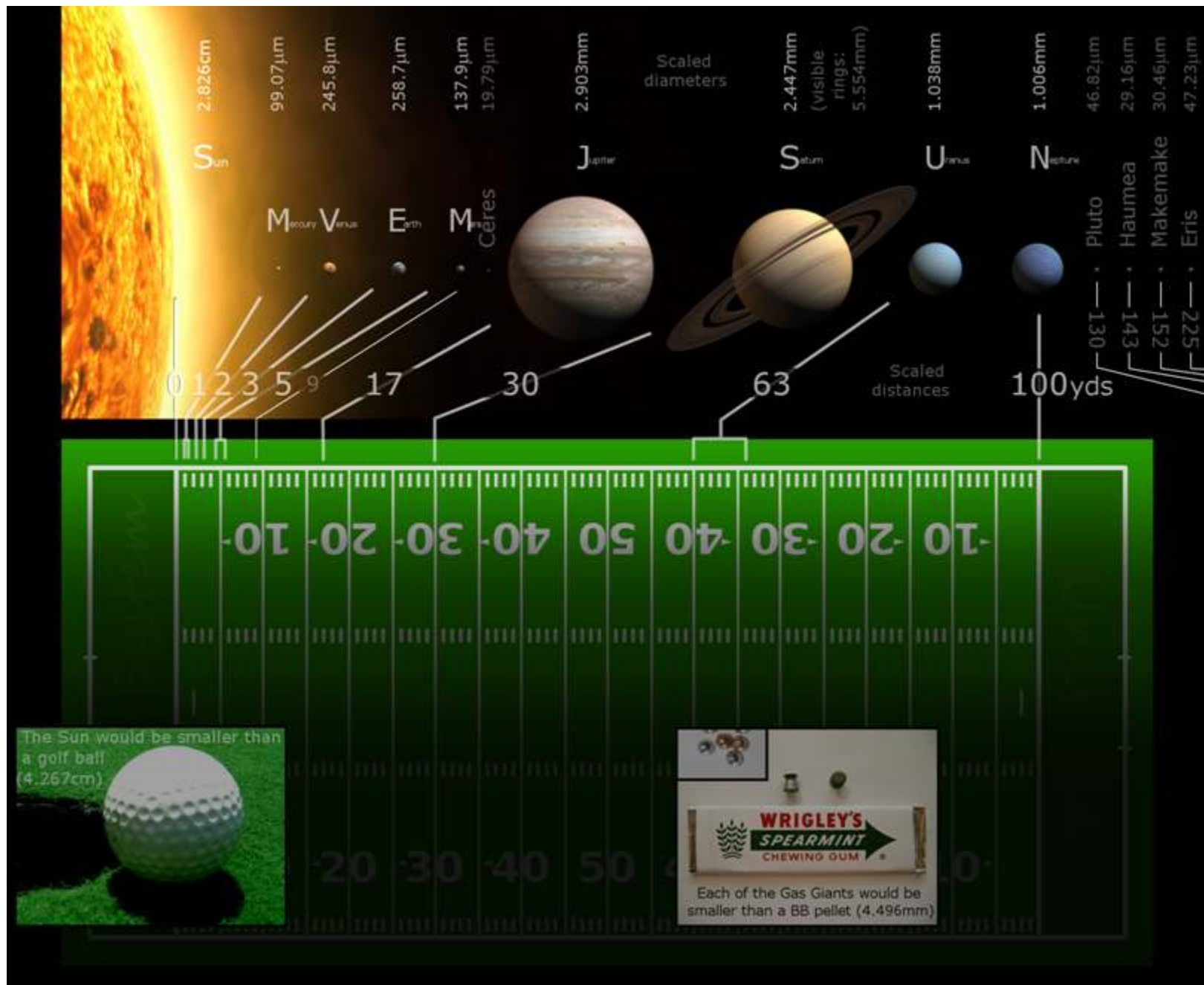
- All objects in the Solar System seem to have formed at nearly the same time, out of the same original cloud of gas and dust
- Radioactive dating of rocks from the Earth, Moon, and some asteroids suggests an age of about 4.5 billion yrs
- A similar age is found for the Sun based on current observations and nuclear reaction rates

Bode's Law

- First noted in 1766, formalized mathematically by **J. E. Bode** in 1778.
- $a = 4 + n$ then divide by 10.
 - 0 3 6 12 24 48 96 192 384
 - 4 7 10 16 28 52 100 196 388
 - 0.4 0.7 1.0 1.6 2.8 5.2 10.0 19.6 38.8
- Does a pretty good job, up to a point in calculating the distances of the planets.

Bode's Calculations

	Planet	2^k	Bode (AU)	Actual (AU)
1	mercury	0	0.4	0.39
2	venus	1	0.7	0.72
3	earth	2	1.	1.
4	mars	4	1.6	1.52
5	asteroids	8	2.8	2.77
6	jupiter	16	5.2	5.2
7	saturn	32	10.	9.54
8	uranus	64	19.6	19.2
9	neptune	128	38.8	30.06
10	pluto	256	77.2	39.44



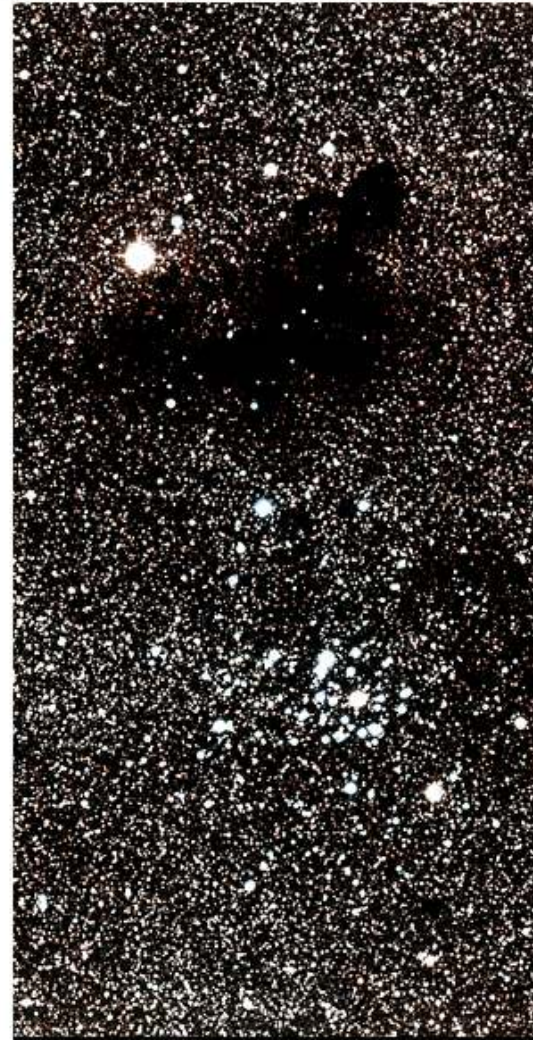
Origin of the Solar System

- A theory of the Solar System's formation must account for the following:
 - Planets orbit in the same direction and in the same plane
 - Rocky inner planets and gaseous/liquid/icy outer planets
 - Compositional trends in the solar system
 - All Solar System bodies appear to be less than 4.5 billion years old
 - Other details – structure of asteroids, cratering of planetary surfaces, detailed chemical composition of surface rocks and atmospheres, etc.

The Solar Nebula Hypothesis

- Derived from 18th century ideas of Laplace and Kant
- Proposes that Solar System evolved from a rotating, flattened disk of gas and dust (an *interstellar cloud*), the outer part of the disk becoming the planets and the inner part becoming the Sun

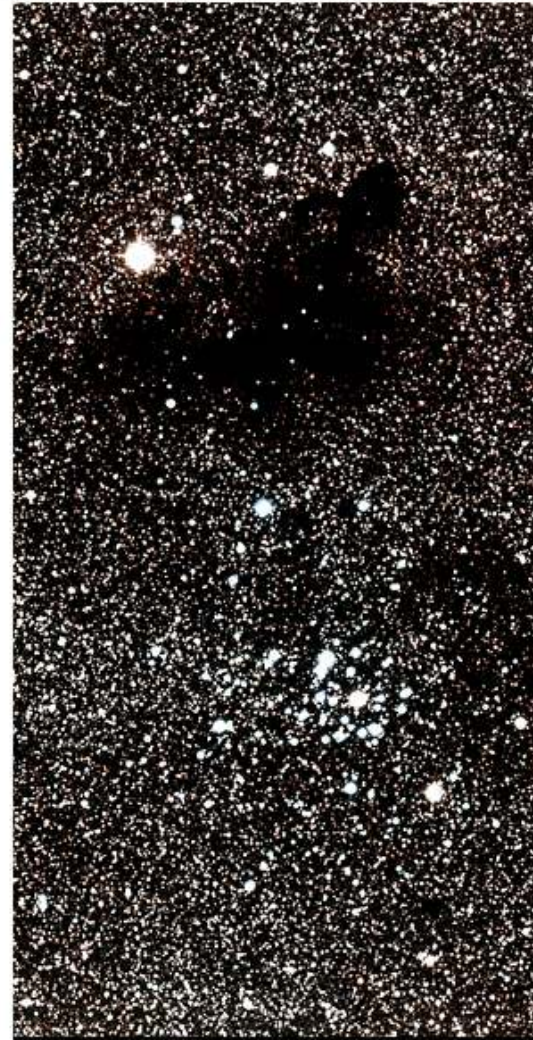
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The Solar Nebula Hypothesis

- This hypothesis naturally explains the Solar System's flatness and the common direction of motion of the planets around the Sun
- Interstellar clouds are common between the stars in our galaxy and this suggests that most stars may have planets around them

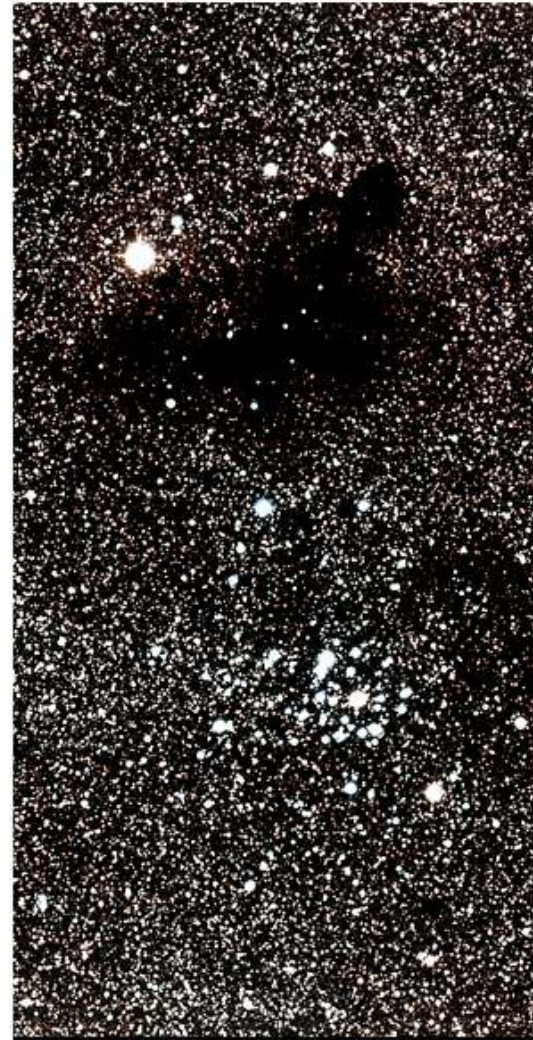
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Interstellar Clouds

- Come in many shapes and sizes – one that formed Solar System was probably a few light years in diameter and 2 solar masses
- Typical clouds are 71% hydrogen, 27% helium, and traces of the other elements

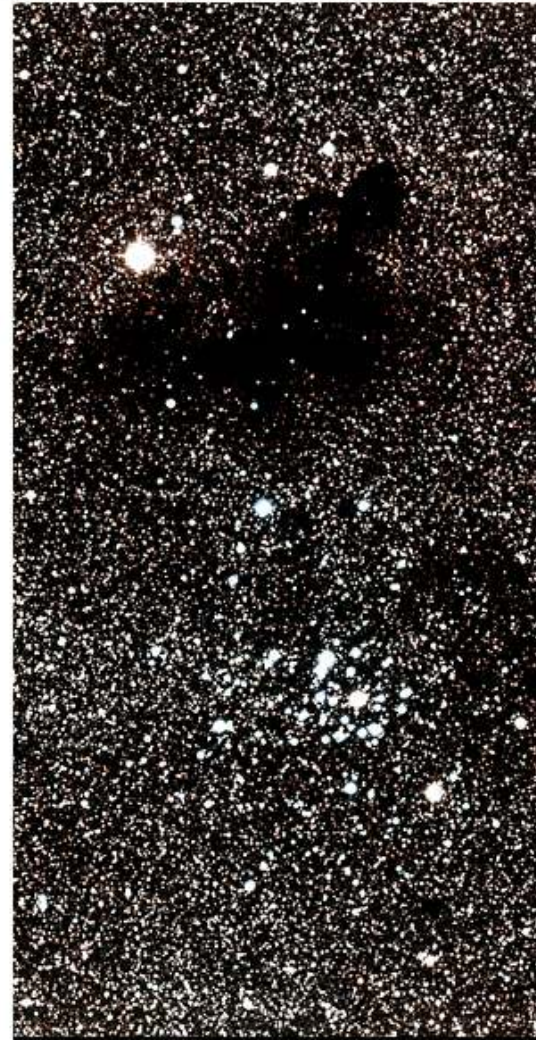
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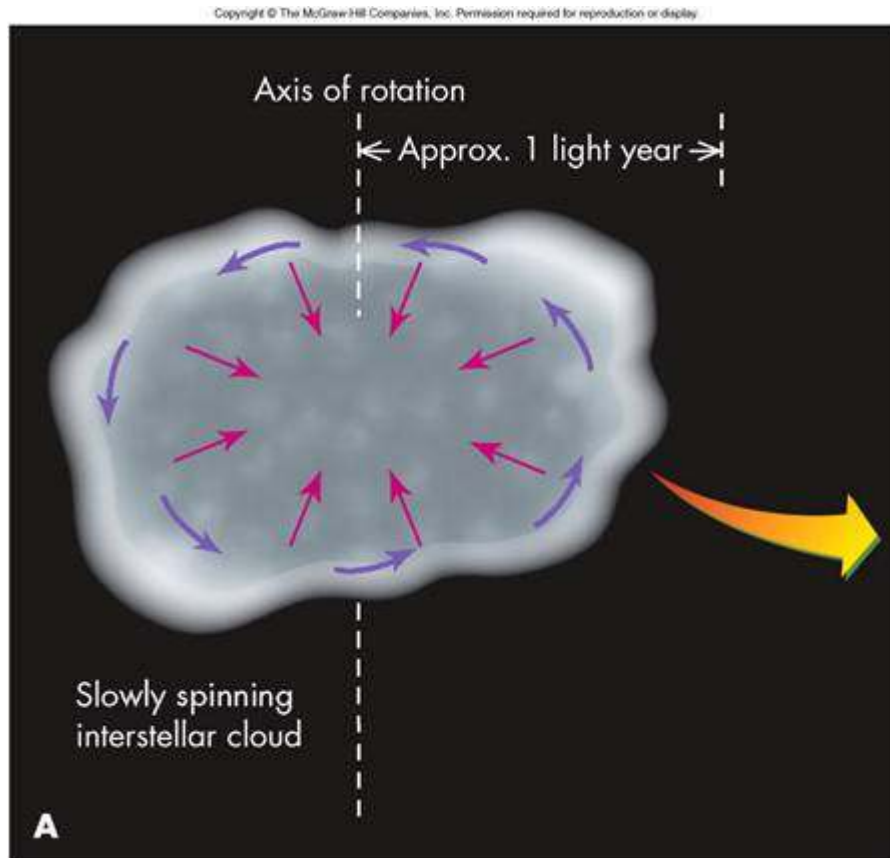
Interstellar Clouds

- Clouds also contain tiny dust particles called *interstellar grains*
 - Grain size from large molecules to a few micrometers
 - They are a mixture of silicates, iron and carbon compounds, and water ice

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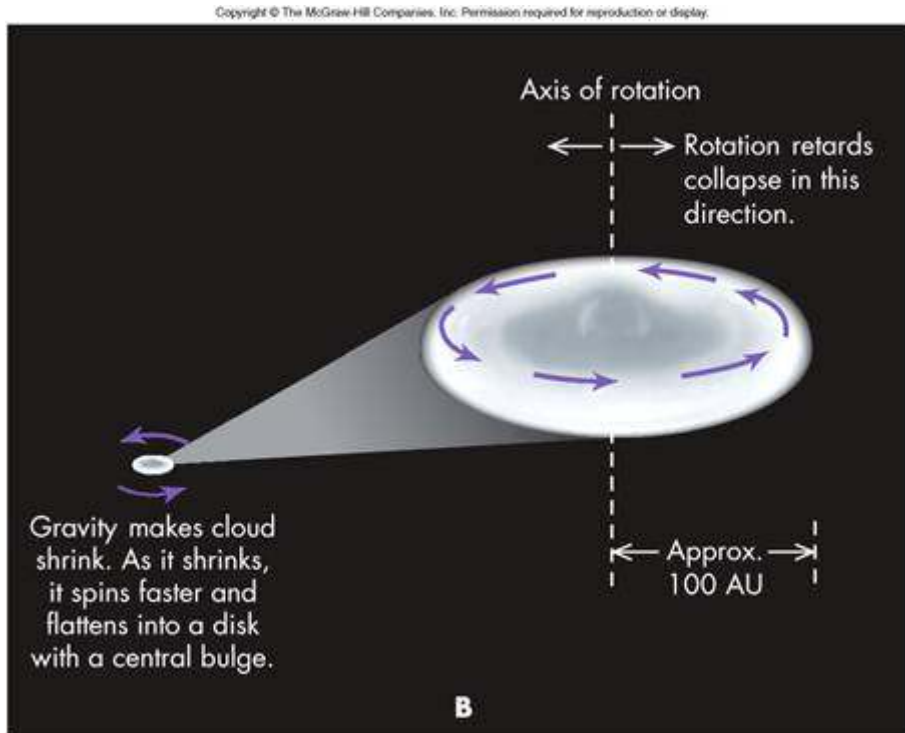


In the Beginning...



- Triggered by a collision with another cloud or a nearby exploding star, rotation forces clouds to gravitationally collapse into a rotating disk

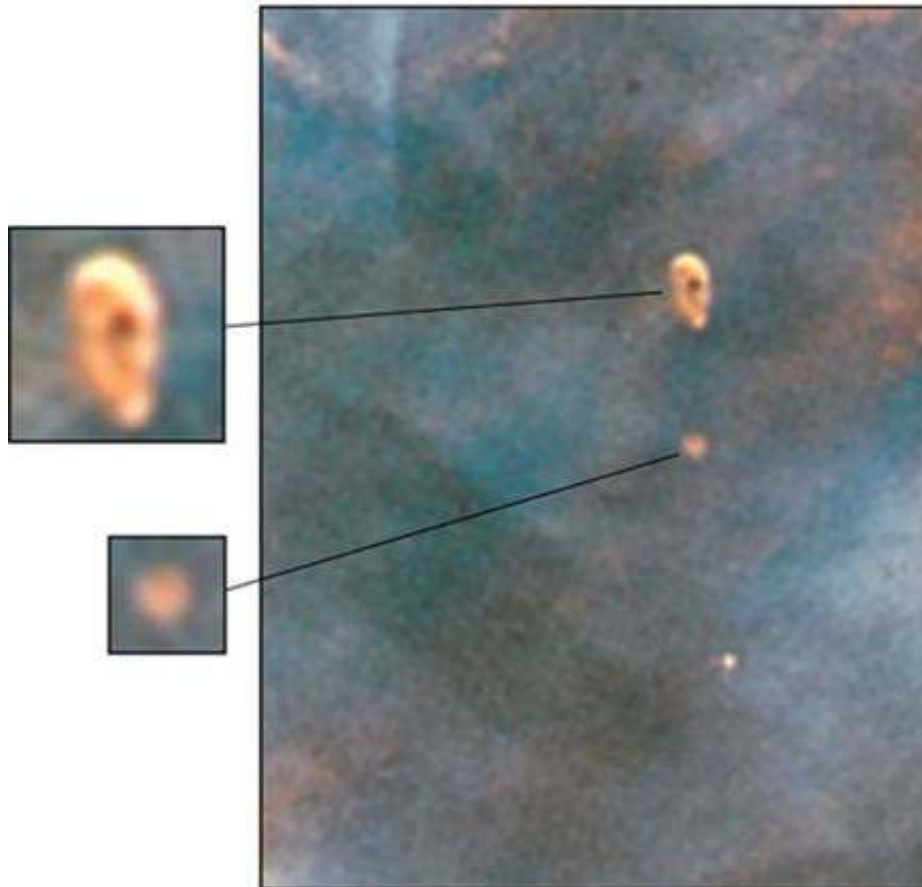
The Solar Nebula



- A few million years pass for a cloud to collapse into a rotating disk with a bulge in the center
- This disk, about **200 AU across and 10 AU thick, is called the *solar nebula*** with the bulge becoming the Sun and the disk condensing into planets

Disk Observations

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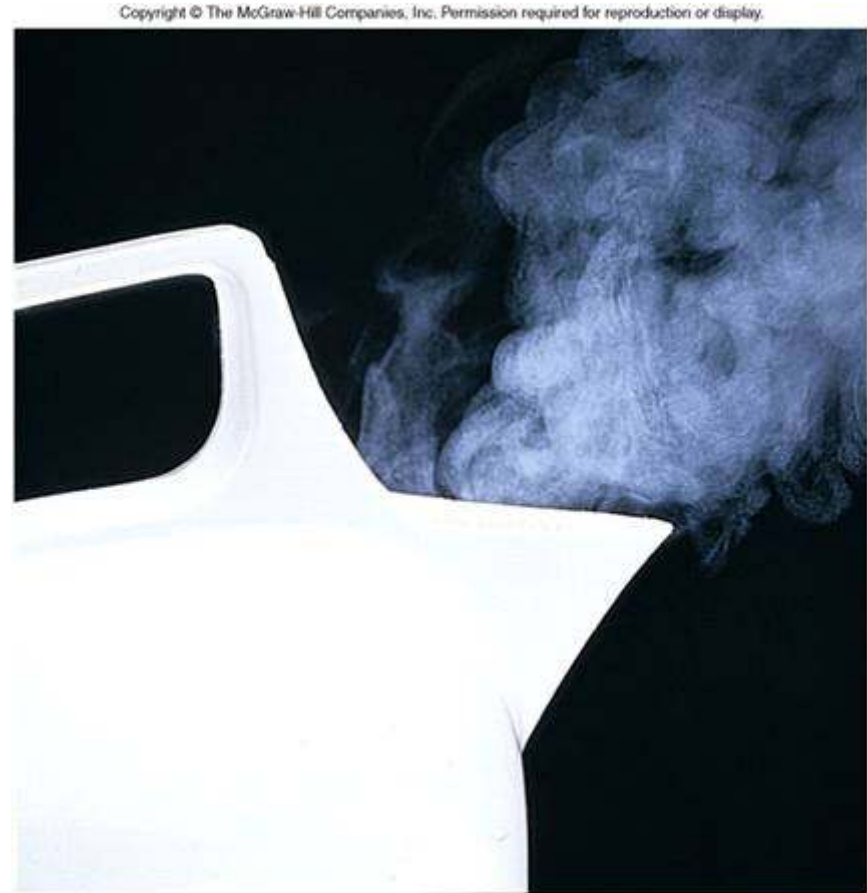


Temperatures in the Solar Nebula

- Before the planets formed, the inner part of the disk was hot, heated by gas falling onto the disk and a young Sun – the outer disk was colder than the freezing point of water

Condensation

- *Condensation* occurs when gas cools below a critical temperature at a given gas pressure and its molecules bind together to form liquid/solid particles

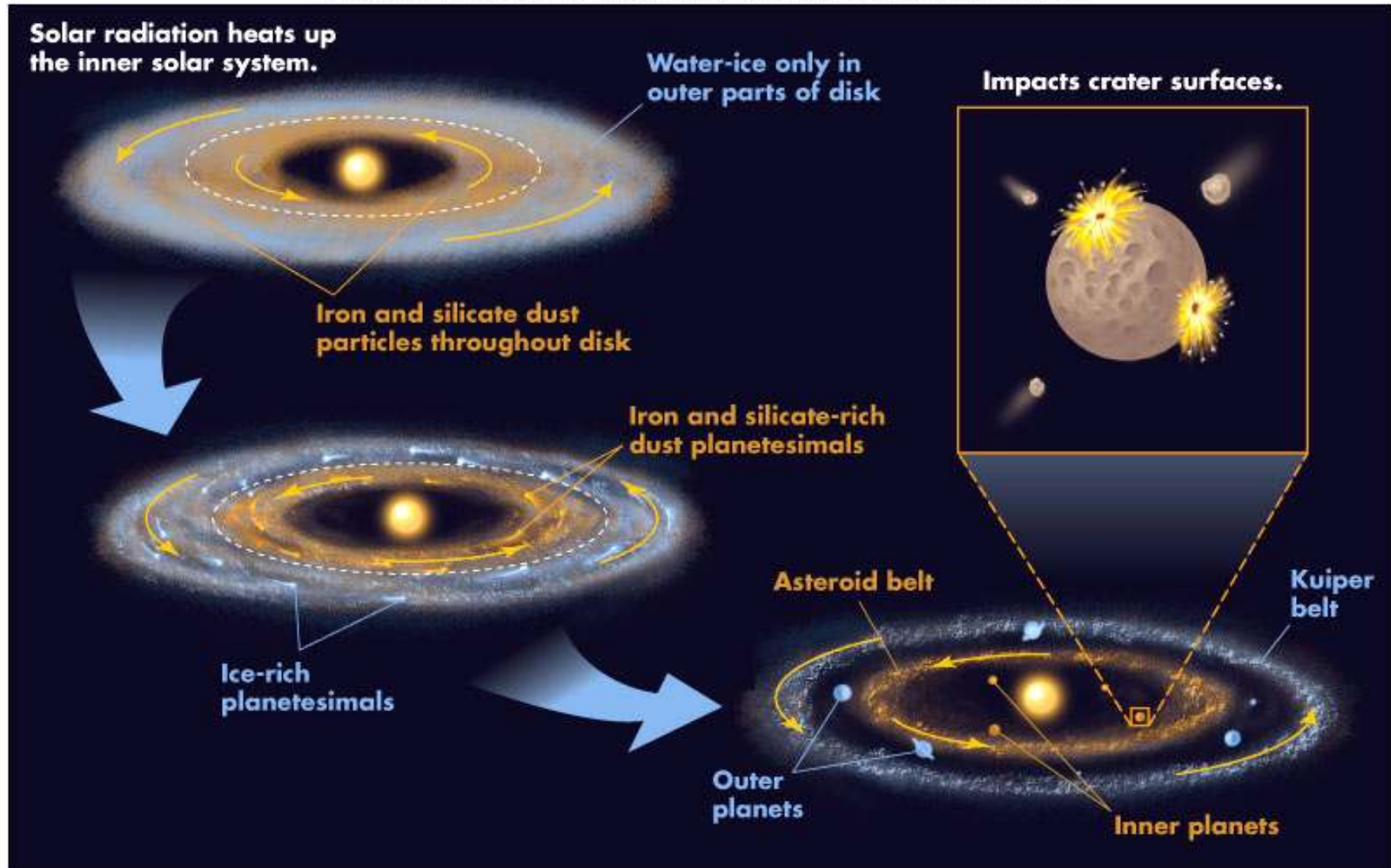


Condensation in the Solar Nebula

- Iron vapor will condense at 1300 K, silicates will condense at 1200 K, and water vapor will condense at room temperature in air
- In a mixture of gases, materials with the highest vaporization temperature condense first
- Condensation ceases when the temperature never drops low enough
- Sun kept inner solar nebula (out to almost Jupiter's orbit) too hot for anything but iron and silicate materials to condense
- Outer solar nebula cold enough for ice to condense

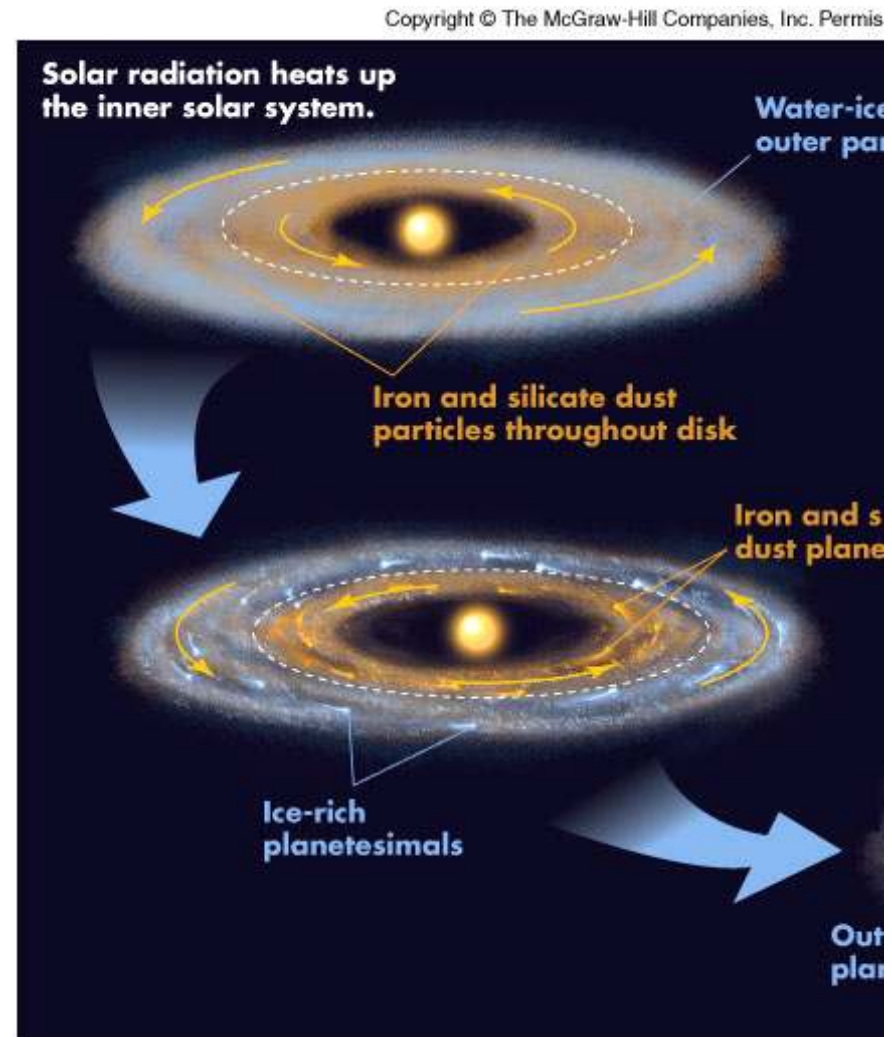
Formation of Planets

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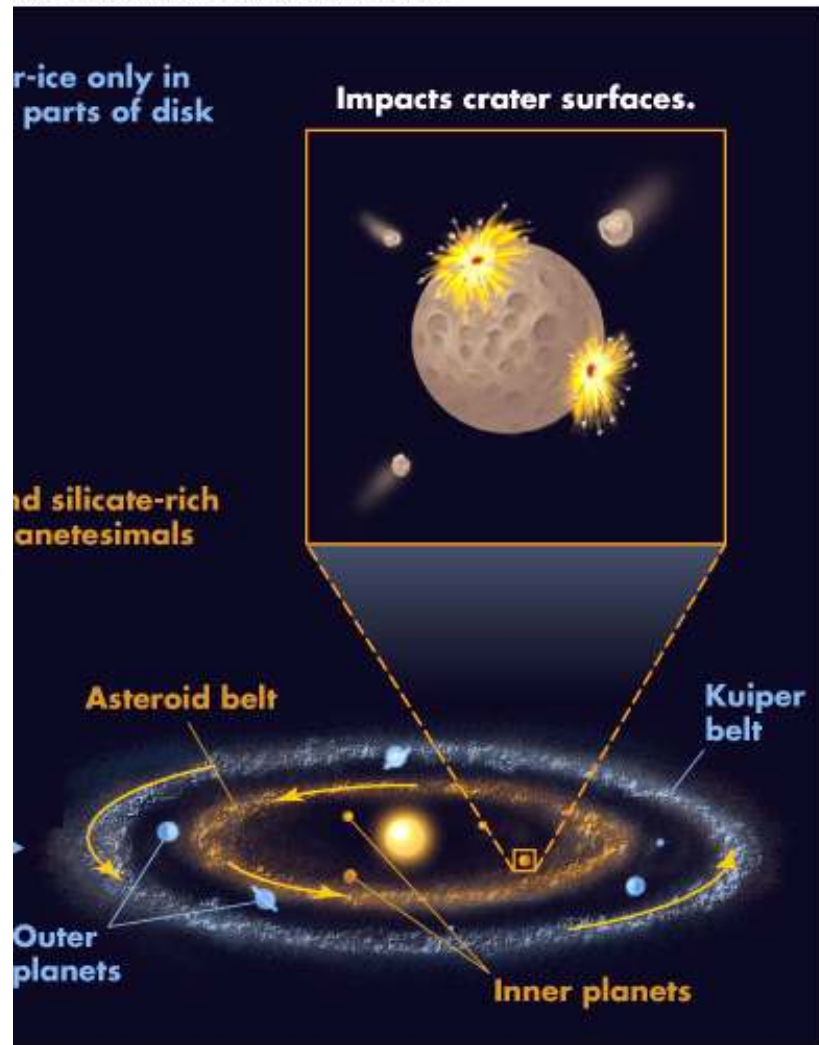
Accretion

- Next step is for the tiny particles to stick together, perhaps by electrical forces, into bigger pieces in a process called *accretion*
- As long as collisions are not too violent, accretion leads to objects, called *planetesimals*, ranging in size from *millimeters* to *kilometers*



Planetesimals

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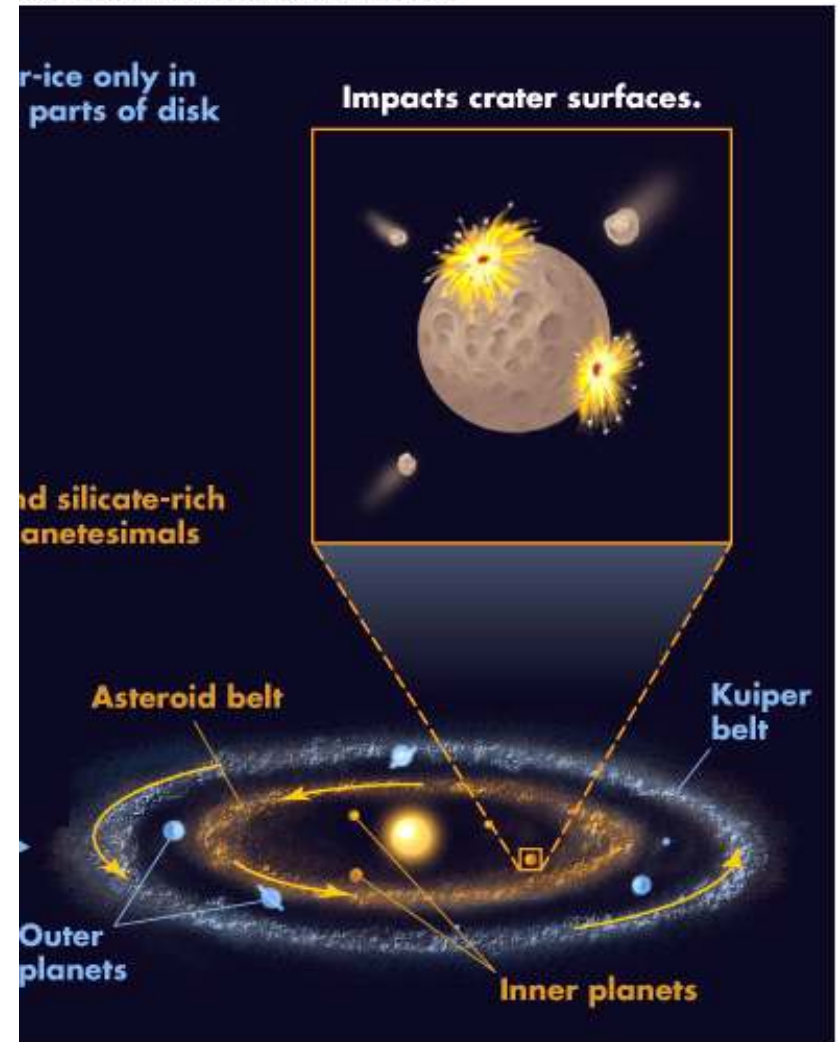


- Planetesimals in the inner solar nebula were rocky-iron composites, while planetesimals in the outer solar nebula were icy-rocky-iron composites
- Planets formed from “gentle” collisions of the planetesimals, which dominated over more violent shattering collisions

Formation of the Planets

- Simulations show that planetesimal collisions gradually lead to approximately circular planetary orbits
- As planetesimals grew in size and mass their increased gravitational attraction helped them grow faster into clumps and rings surrounding the Sun

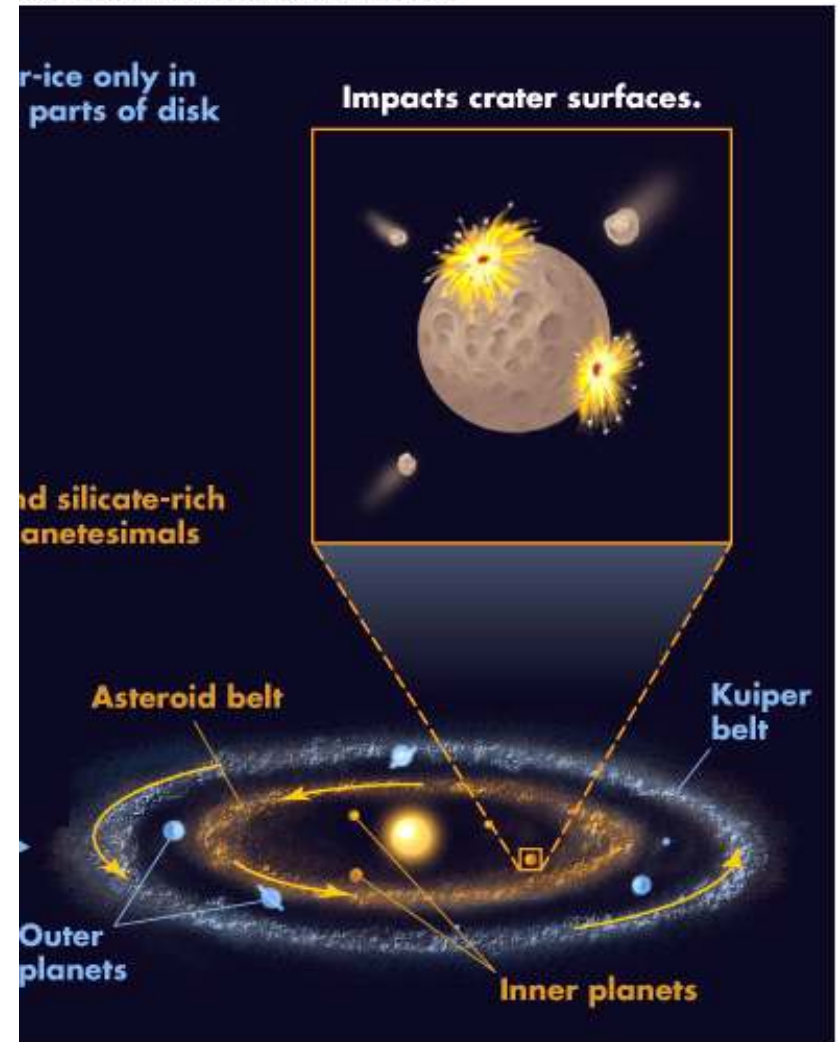
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Formation of the Planets

- Planet growth was especially fast in the outer solar nebula due to:
 - Larger volume of material to draw upon
 - Larger objects (bigger than Earth) could start gravitationally capturing gases like H and He

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Continuous Bombardment

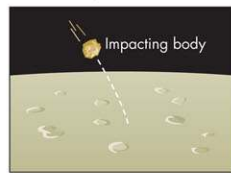
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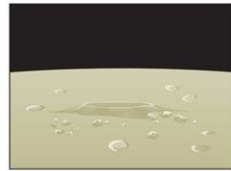
Mercury



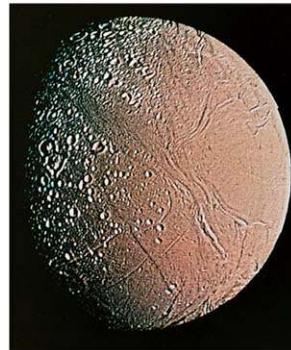
Manicouagan Crater on Earth



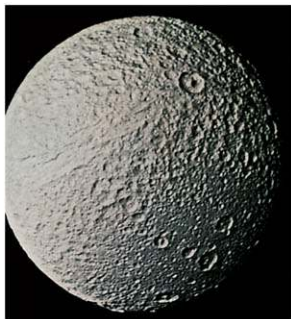
Mars



Dione



Enceladus



Tethys



Titania

- Continued planetesimal bombardment and internal radioactivity melted the planets and led to the density differentiation of planetary interiors

Formation of Moons

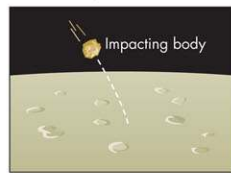
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Mercury



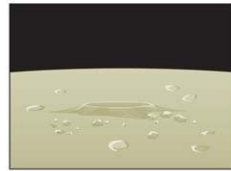
Manicouagan Crater on Earth



Dione



Mars



Enceladus



Tethys



Titania

- Moons of the outer planets were probably formed from planetesimals orbiting the growing planets
- Not large enough to capture H or He, the outer moons are mainly rock and ice giving them solid surfaces

Final Stages

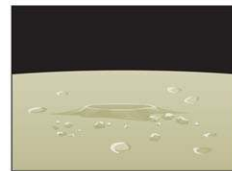
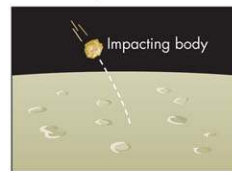
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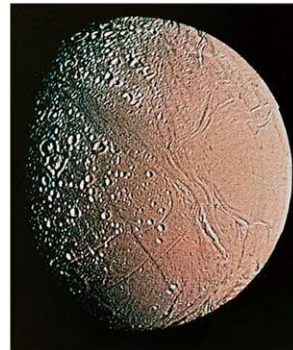
Mercury



Manicouagan Crater on Earth



Dione



Enceladus



Tethys



Titania

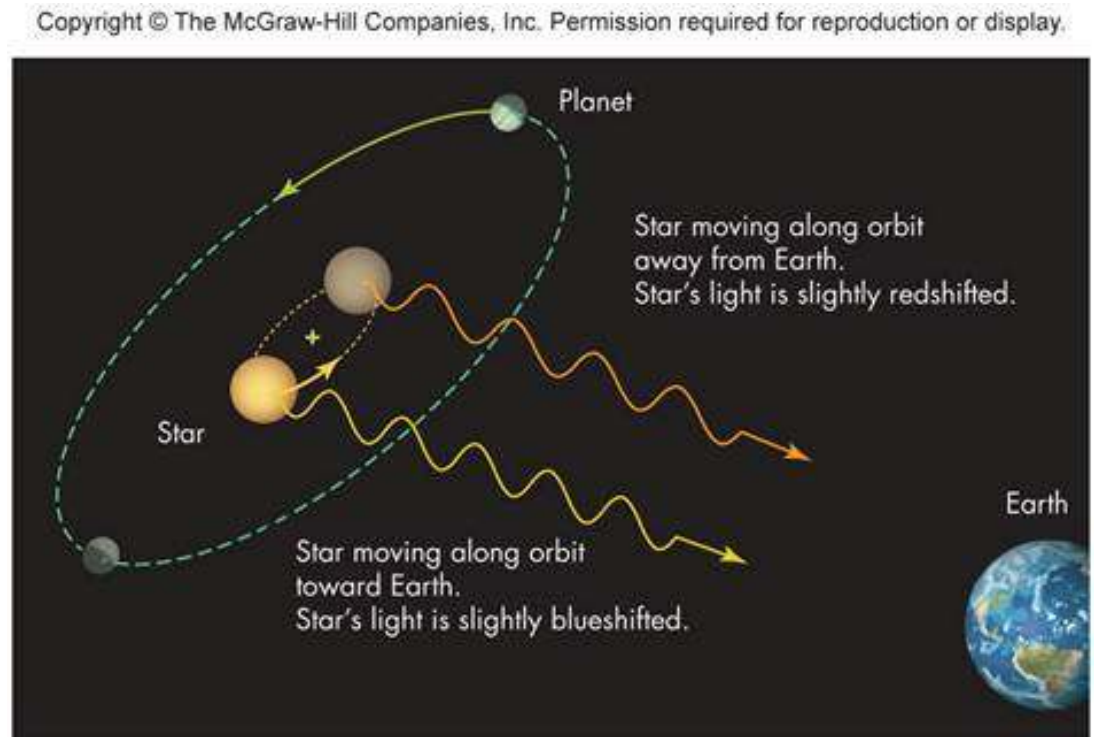
- Rain of planetesimals cratered surfaces
- Remaining planetesimals became small moons, comets, and asteroids

Formation of Atmospheres

- Atmospheres were the last planet-forming process
- Outer planets gravitationally captured their atmospheres from the solar nebula
- Inner planets created their atmospheres by volcanic activity and perhaps from comets and asteroids that vaporized on impact
- Objects like Mercury and the Moon are too small – not enough gravity – to retain any gases on their surfaces

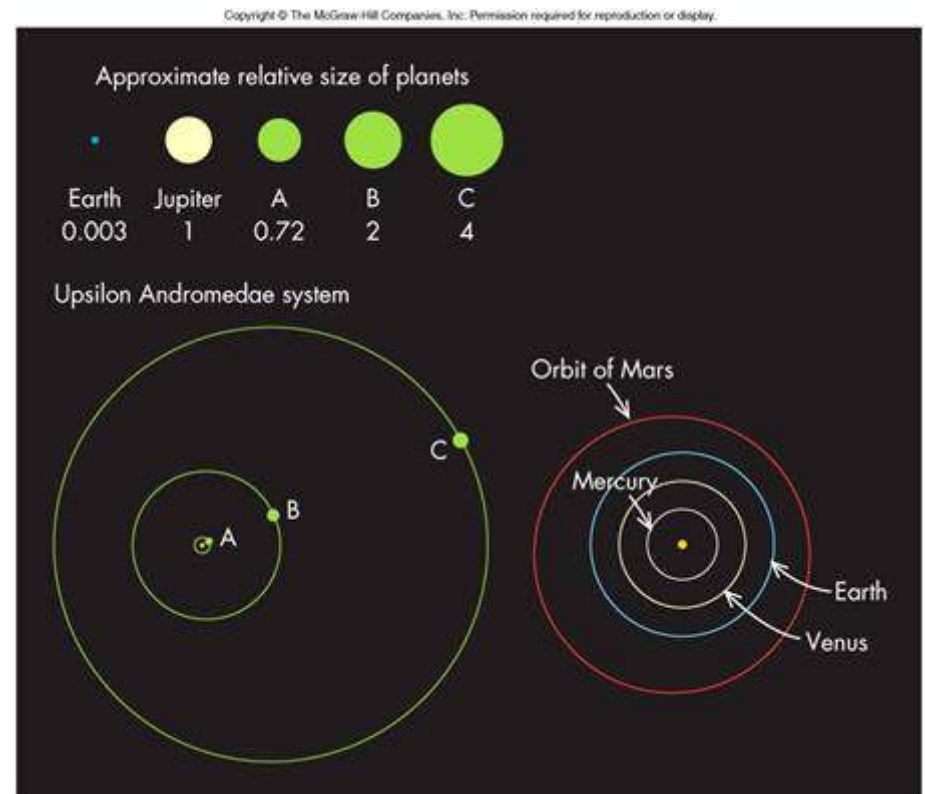
Exosolar Planets

- Evidence exists for planets around other nearby stars
- The new planets are not observed directly, but rather by their gravitational effects on their parent star
- These new planets are a surprise - they have huge planets very close to their parent stars



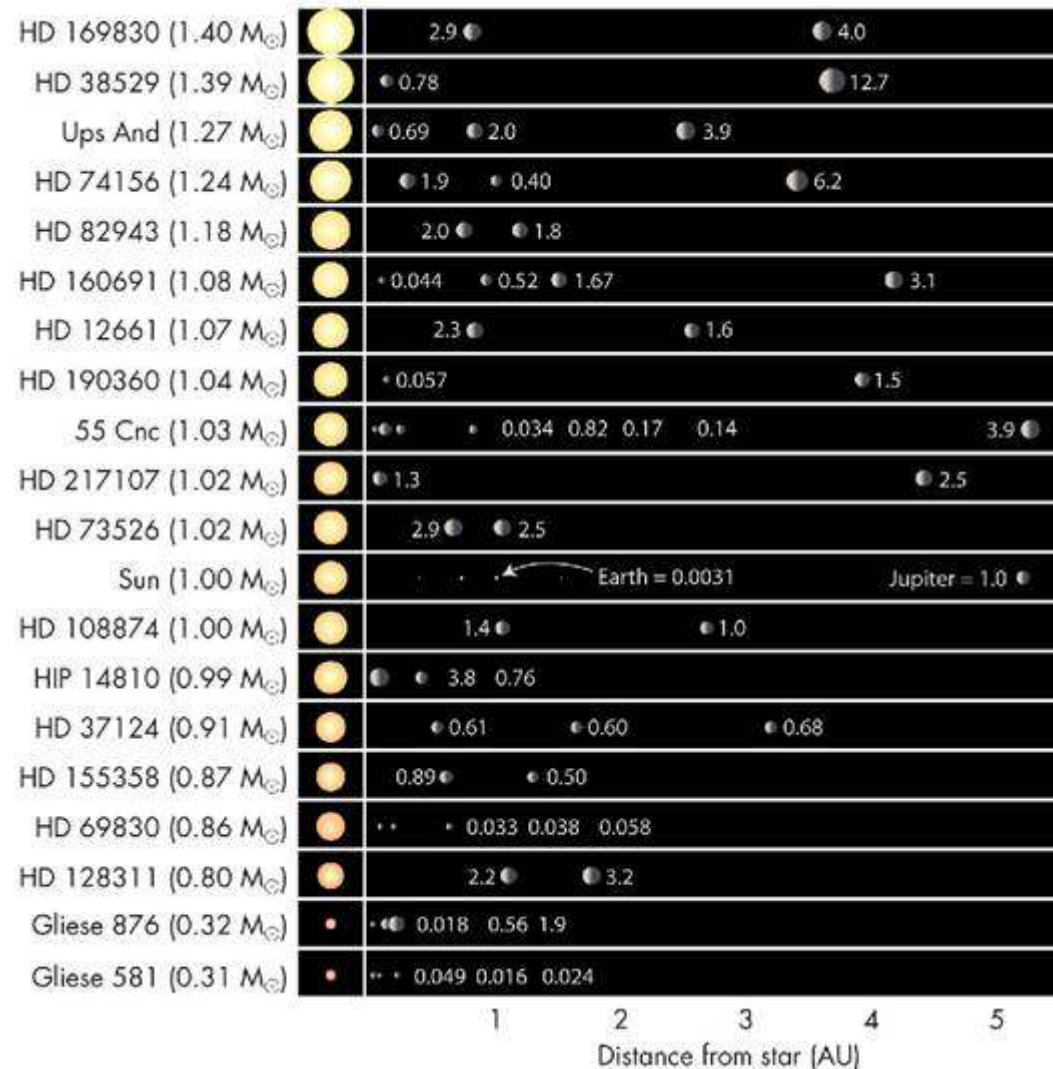
Exosolar Planets

- Idea: The huge planets formed far from their stars as current theory would project, but their orbits subsequently shrank
- This migration of planets may be caused by interactions between forming planets and leftover gas and dust in the disk



A Sample of Exoplanets

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Exoplanet App!