The Origin of the Solar System

The Great Chain of Origins: Early Hypotheses

1) Catastrophic hypotheses

Example: passing star hypothesis:

Star passing the sun closely tore material out of the sun, from which planets could form (no longer considered)

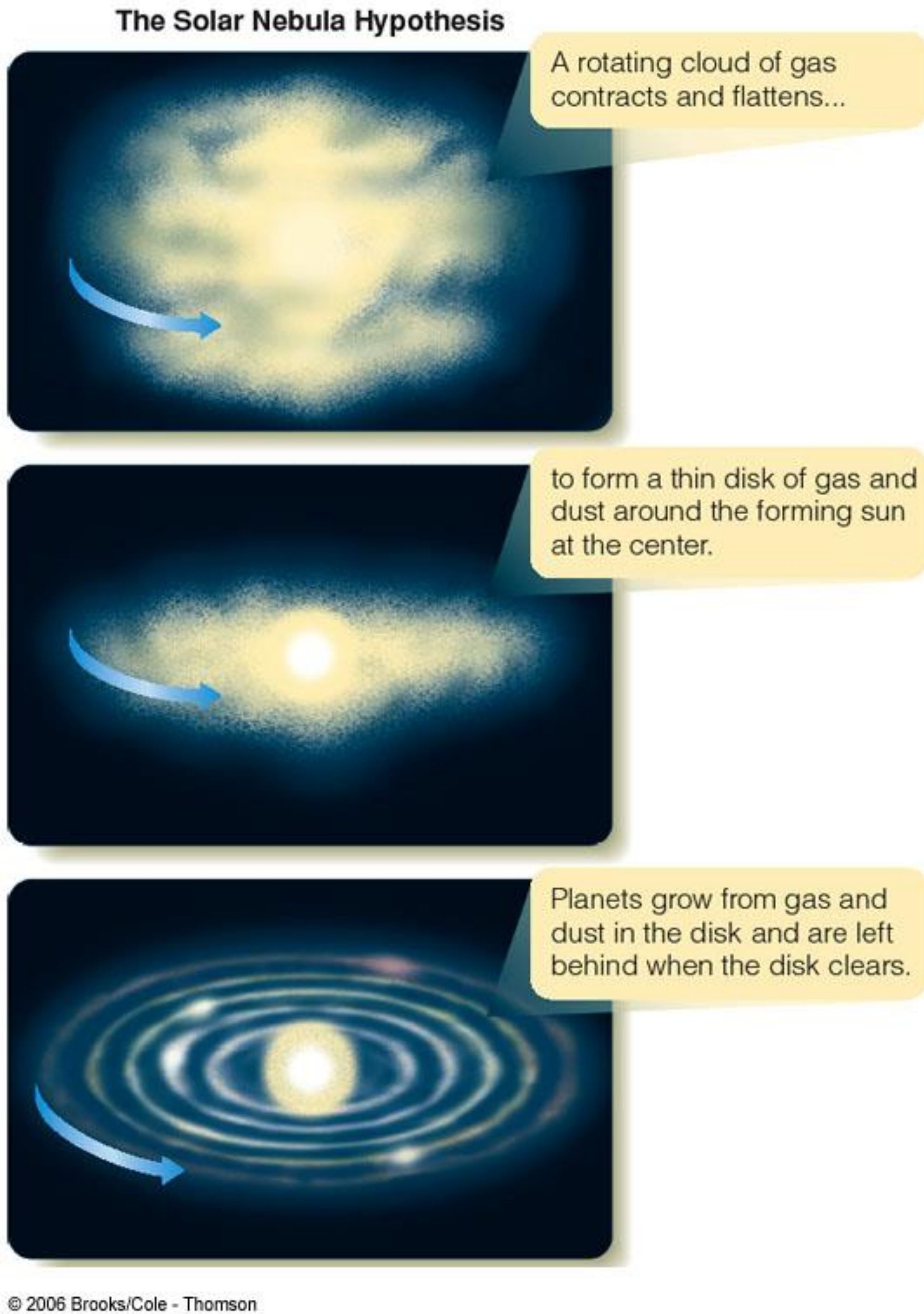
Catastrophic hypotheses predict:
Only few stars should have planets!

2) Evolutionary hypotheses

Example: Laplace's nebular hypothesis:

Rings of material separate from the spinning cloud, carrying away angular momentum of the cloud $\rightarrow$ cloud could contract further (forming the sun)

Evolutionary hypotheses predict:
Most stars should have planets!



The Solar Nebula Hypothesis

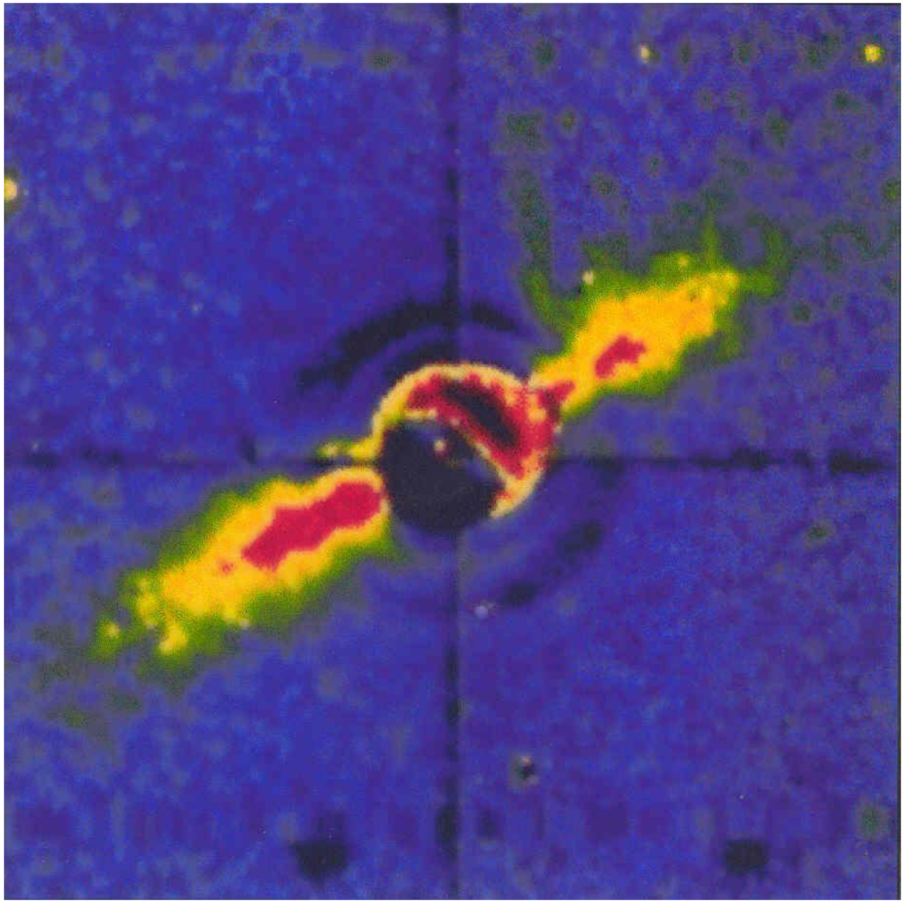
Basis of modern theory of planet formation.

Planets form at the same time from the same cloud as the star.

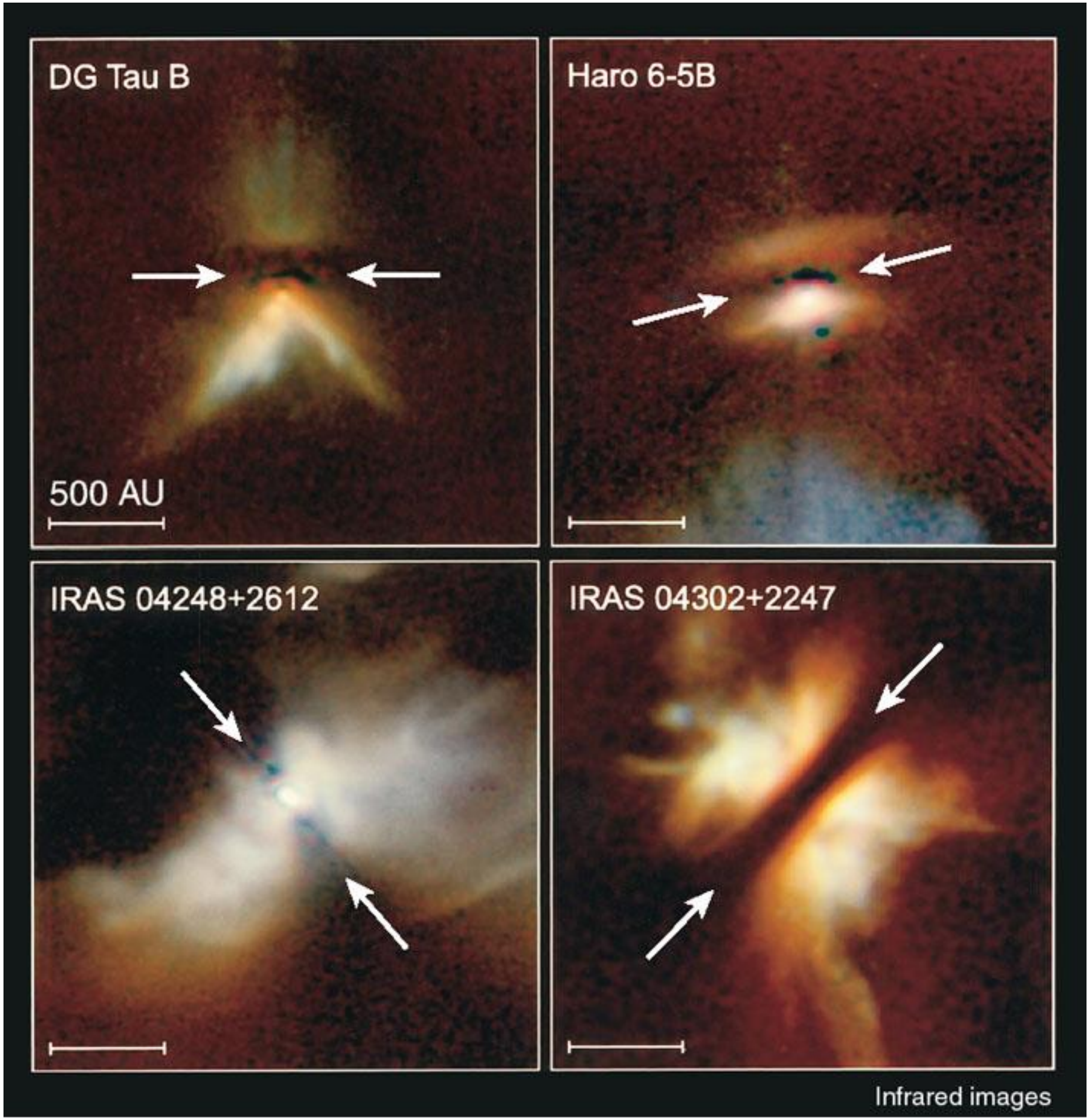
Planet formation sites observed today as dust disks of T Tauri stars- very young stars having a mass of the same order of the Sun

Sun and our solar system formed ~ 5 billion years ago.

Star dust disk



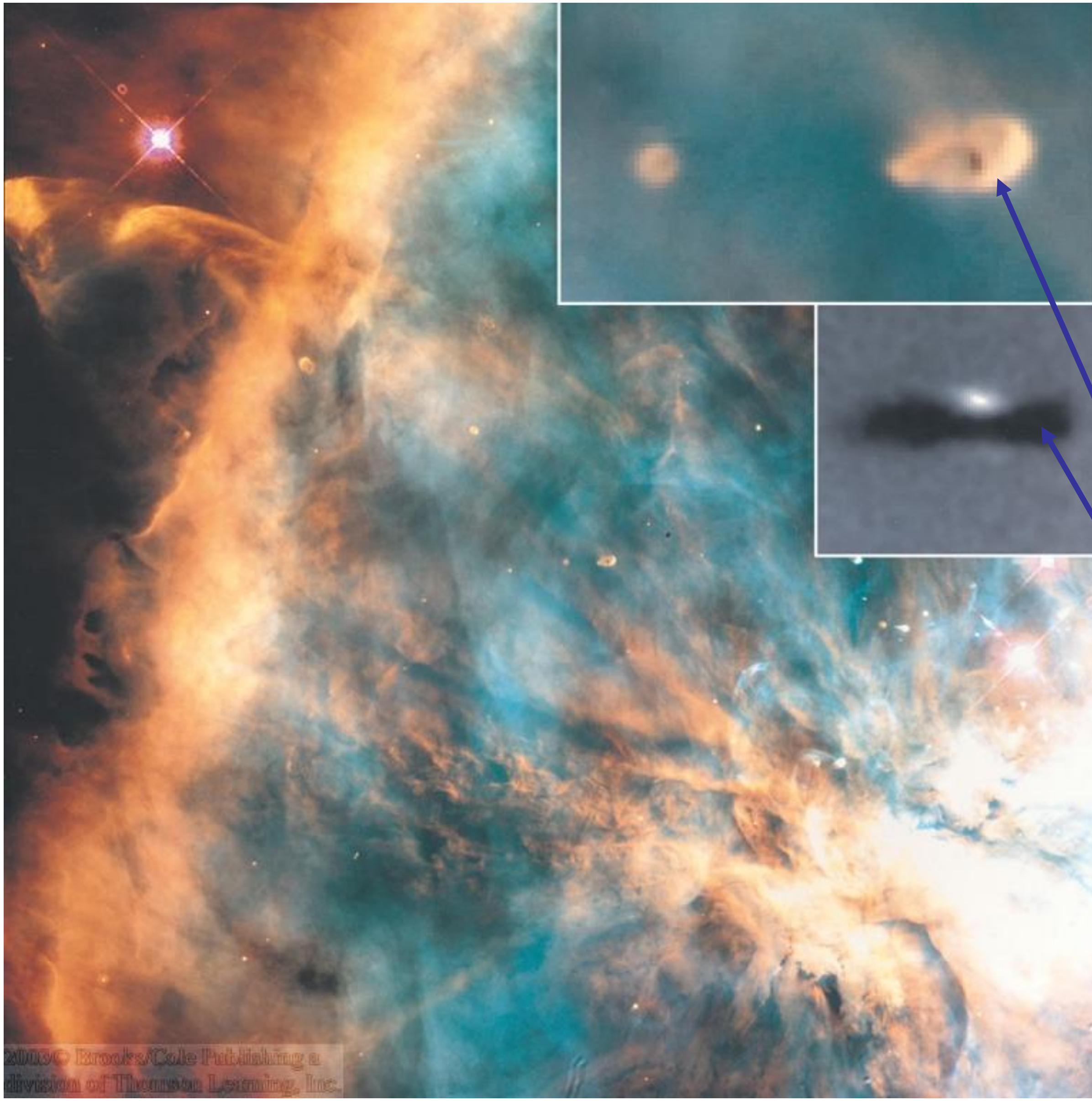
Beta Pictoris



Dust Disks around Forming Stars

Dust disks around some T Tauri stars can be imaged directly using Hubble Space Telescope

Evidence for Ongoing Planet Formation



Many young stars in the Orion Nebula are surrounded by dust disks:

Probably sites of planet formation right now!

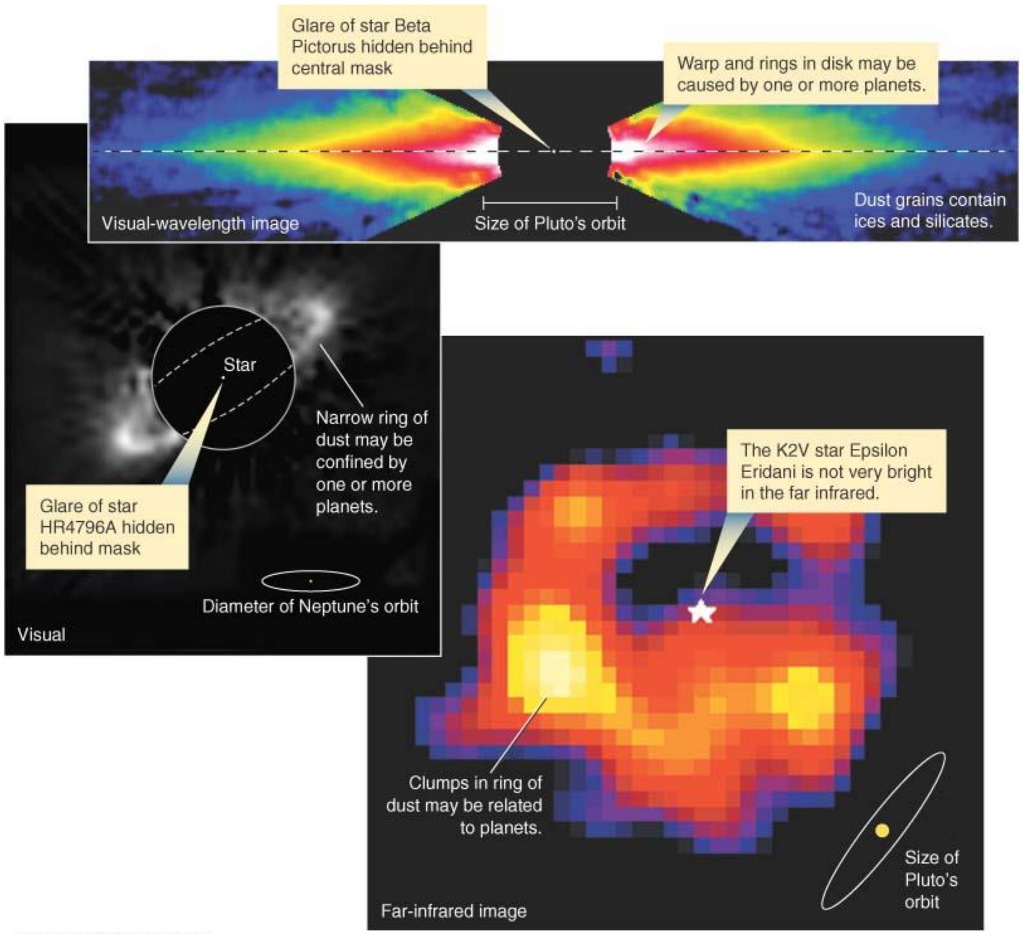
Orion Nebula is a diffuse nebula situated in the Milky Way Galaxy, being south of Orion’s Belt in the constellation of Orion

Extrasolar Planets

Modern theory of planet formation is evolutionary

→ Many stars should have planets!

→ planets orbiting around other stars = "Extrasolar planets"

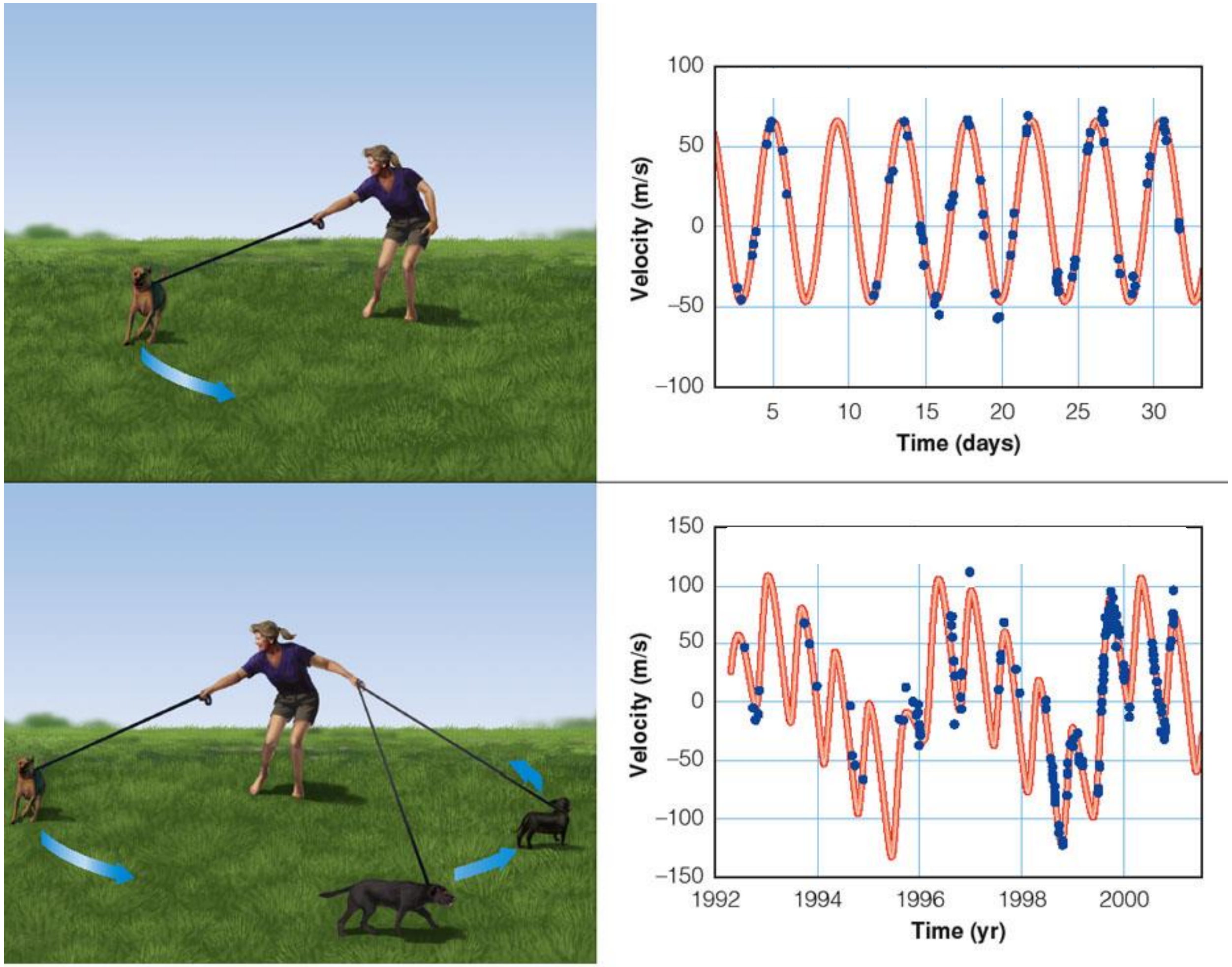


Extrasolar planets can not be imaged directly.

Detection using same methods as in binary star systems:

Look for "wobbling" motion of the star around the common center of mass.

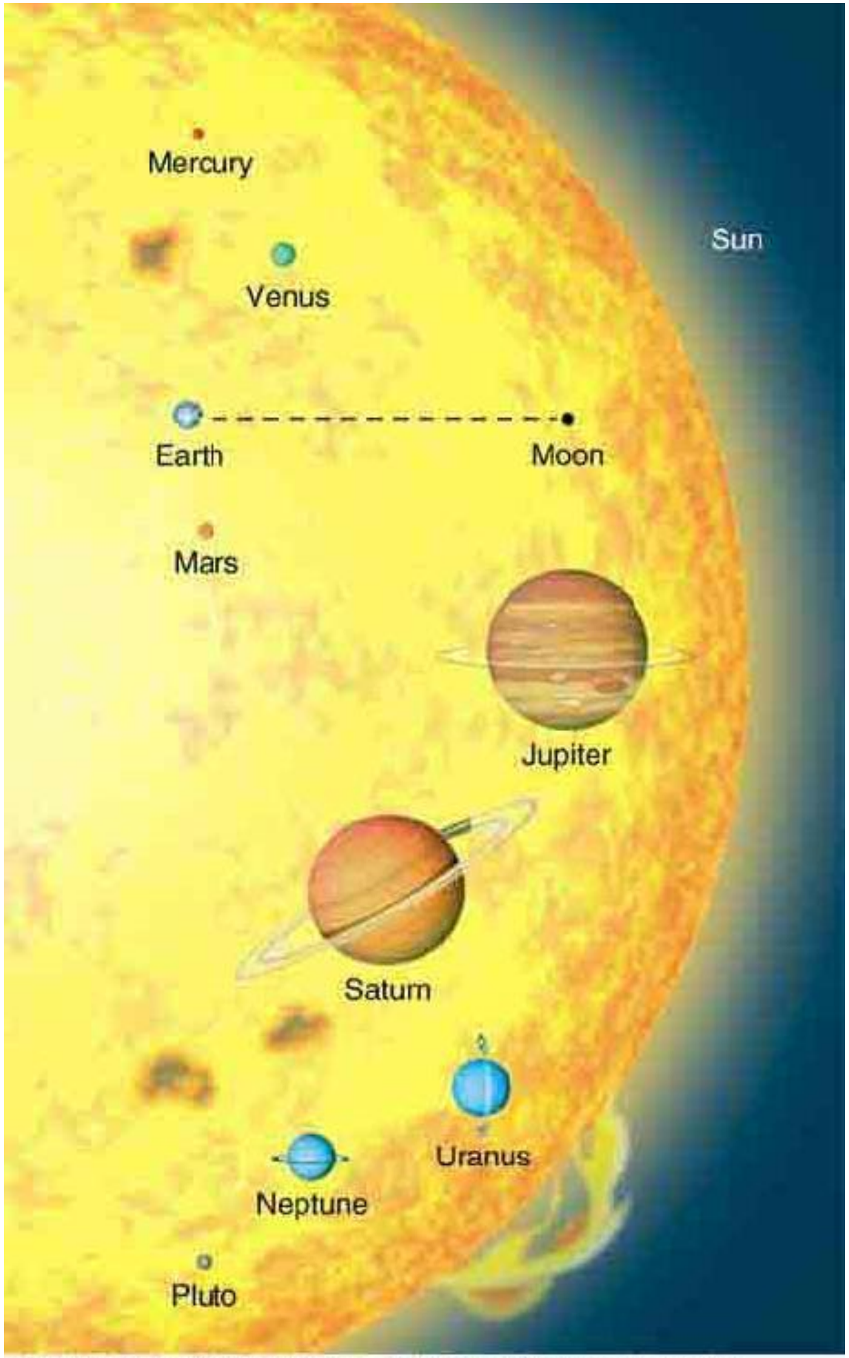
Indirect Detection of Extrasolar Planets



Observing periodic Doppler shifts of stars with no visible companion:

Evidence for the wobbling motion of the star around the common center of mass of a planetary system

Over 100 extrasolar planets detected so far.



Survey of the Solar System

Relative Sizes of the Planets

Assume, we reduce all bodies in the solar system so that the Earth has diameter 0.3 mm.

Sun: ~ size of a small plum.

Mercury, Venus, Earth, Mars: ~ size of a grain of salt.

Jupiter: ~ size of an apple seed.

Saturn: ~ slightly smaller than Jupiter's "apple seed".

Uranus, Neptune: ~ Larger salt grains.

Pluto: ~ Speck of pepper.

Planetary Orbits

All planets in almost circular (elliptical) orbits around the sun, in approx. the same plane (ecliptic).

Sense of revolution: counter-clockwise

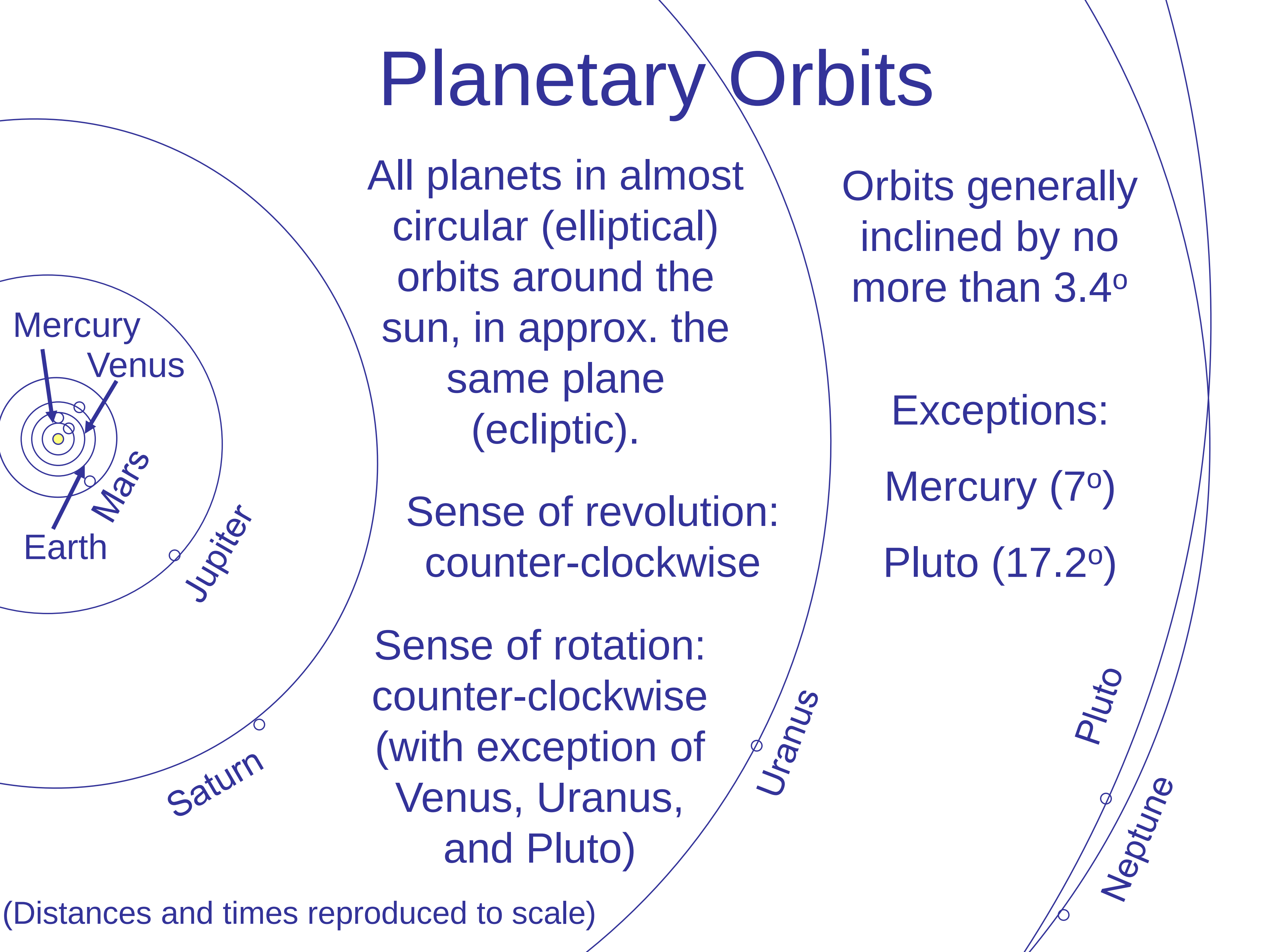
Sense of rotation: counter-clockwise (with exception of Venus, Uranus, and Pluto)

Orbits generally inclined by no more than 3.4º

Exceptions:

Mercury (7º)

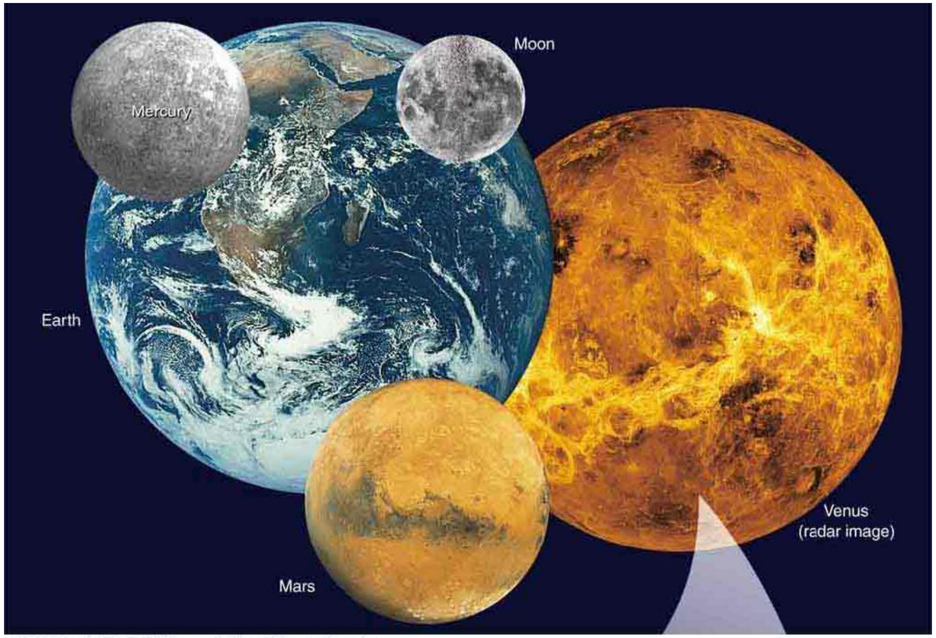
Pluto (17.2º)



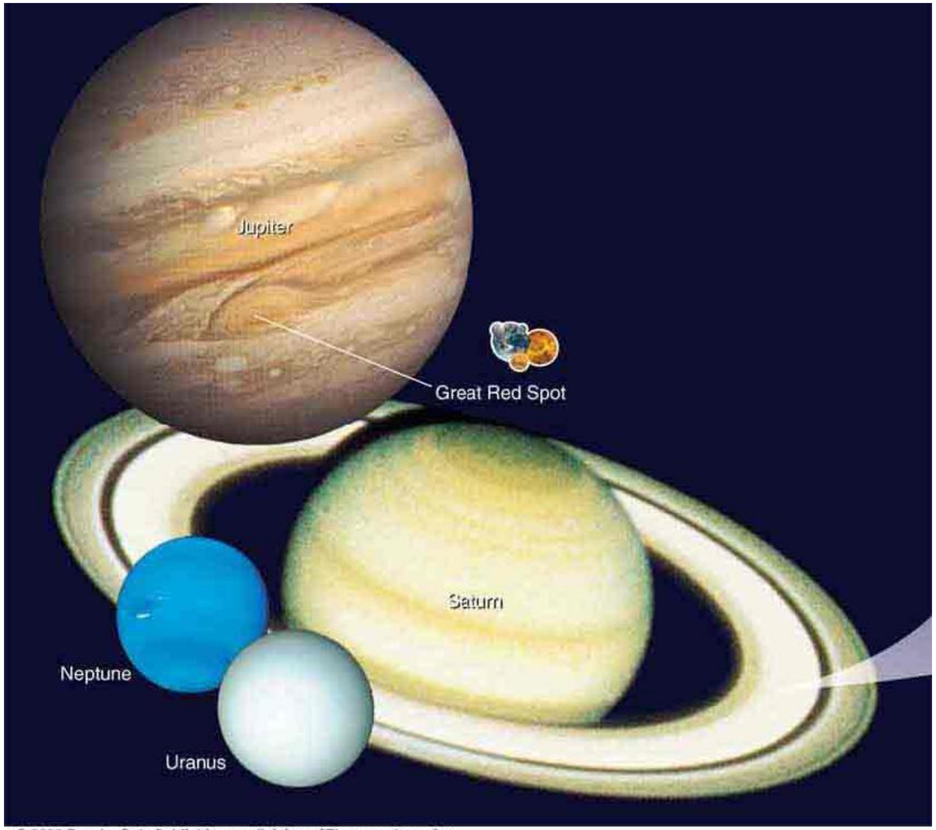
(Distances and times reproduced to scale)

Two Kinds of Planets

Planets of our solar system can be divided into two very different kinds:



Terrestrial (earthlike) planets:
Mercury, Venus, Earth, Mars



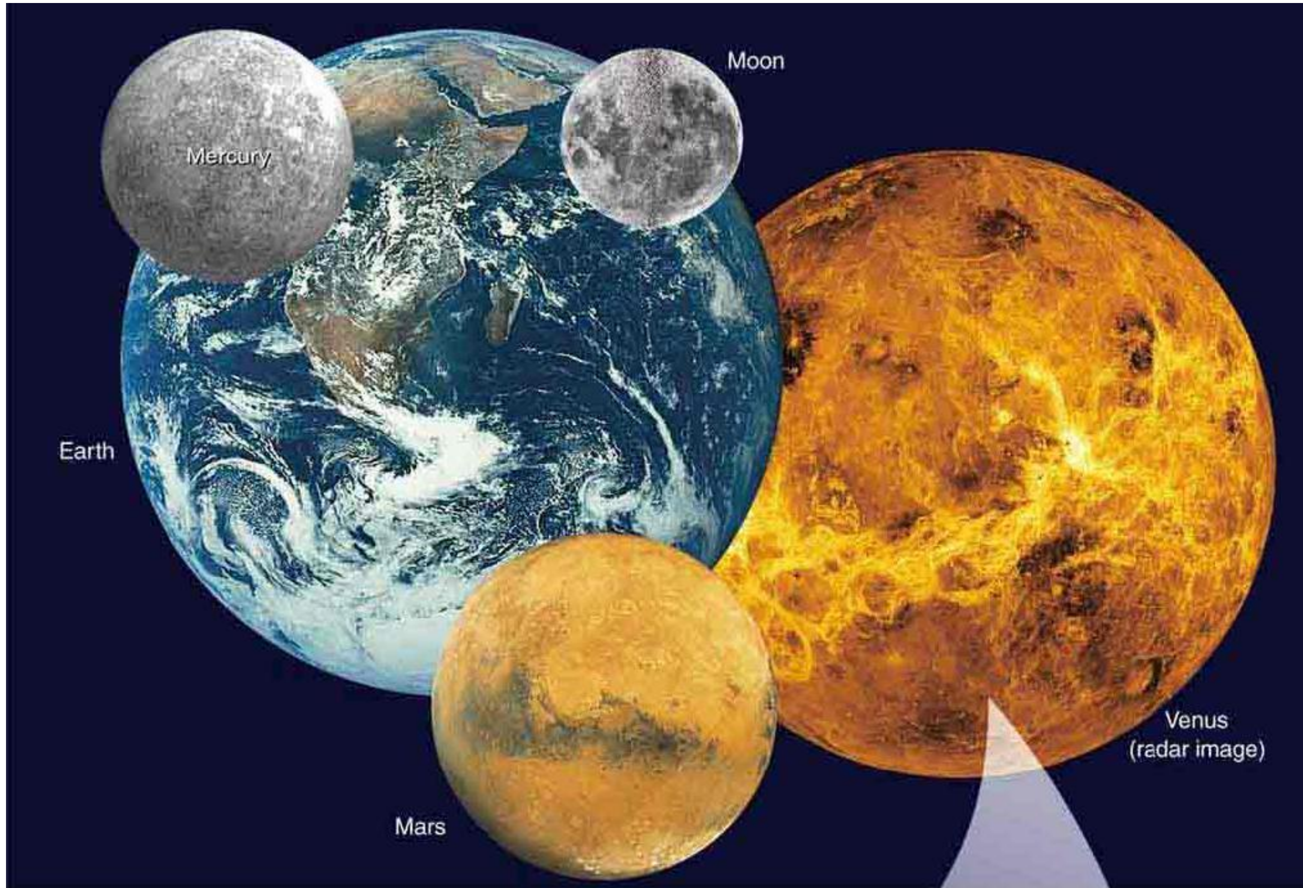
Jovian (Jupiter-like) planets:
Jupiter, Saturn, Uranus, Neptune

Terrestrial Planets

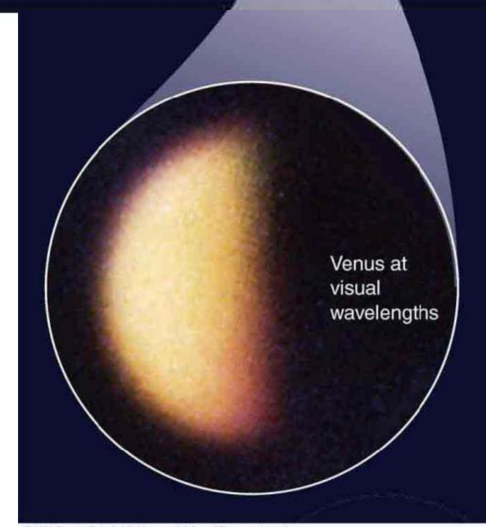
Four inner planets of the solar system

Relatively small in size and mass (Earth is the largest and most massive)

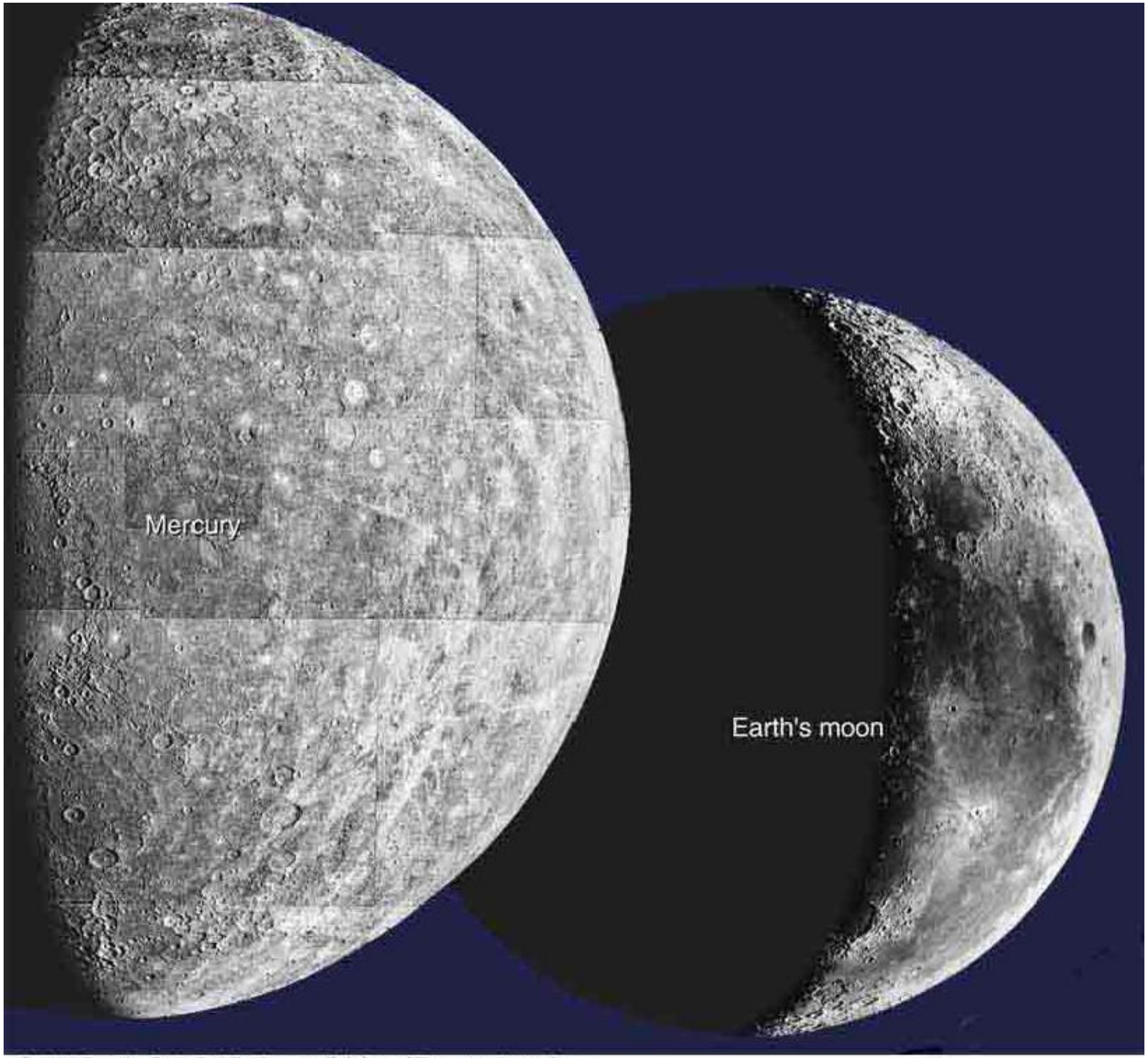
Rocky surface



Surface of Venus can not be seen directly from Earth because of its dense cloud cover.



Craters on Planets' Surfaces



Craters (like on our moon's surface) are common throughout the solar system.

Not seen on Jovian planets because they don't have a solid surface.

The Story of Planet Building

Planets formed from the same protostellar material as the sun, still found in the sun's atmosphere.

Rocky planet material formed from clumping together of dust grains in the protostellar cloud.

Mass of less than ~ 15 Earth masses:

Planets can not grow by gravitational collapse

Earthlike planets

Mass of more than ~ 15 Earth masses:

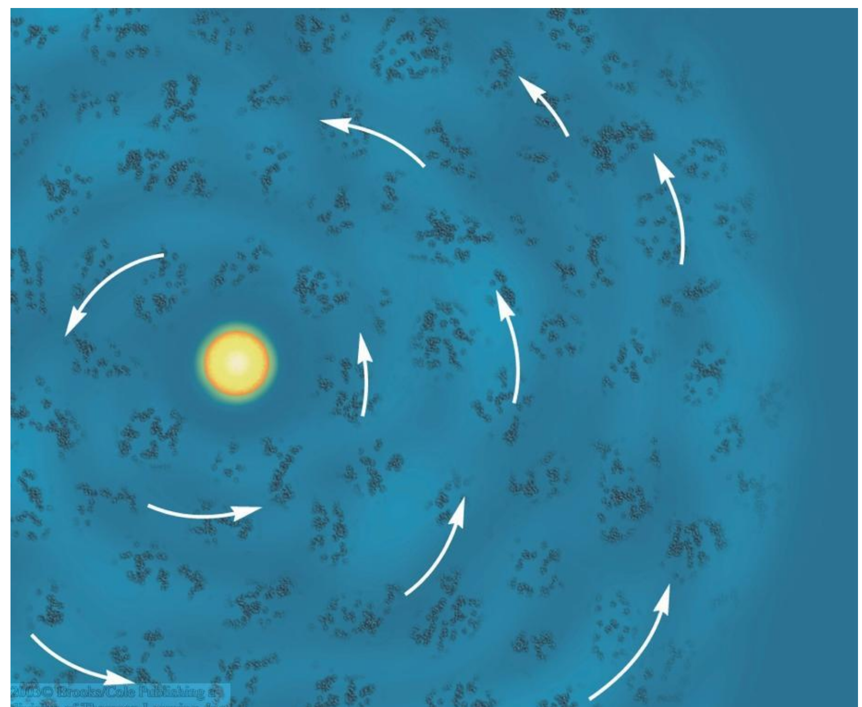
Planets can grow by gravitationally attracting material from the protostellar cloud

Jovian planets (gas giants)

Planet Formation and Growth of Planetesimals

Planet formation starts with clumping together of grains of solid matter: planetesimals

Planetesimals (few cm to km in size) collide to form planets.



Planetesimal growth through condensation and accretion.

Gravitational instabilities may have helped in the growth of planetesimals into protoplanets.

The Condensation of Solids

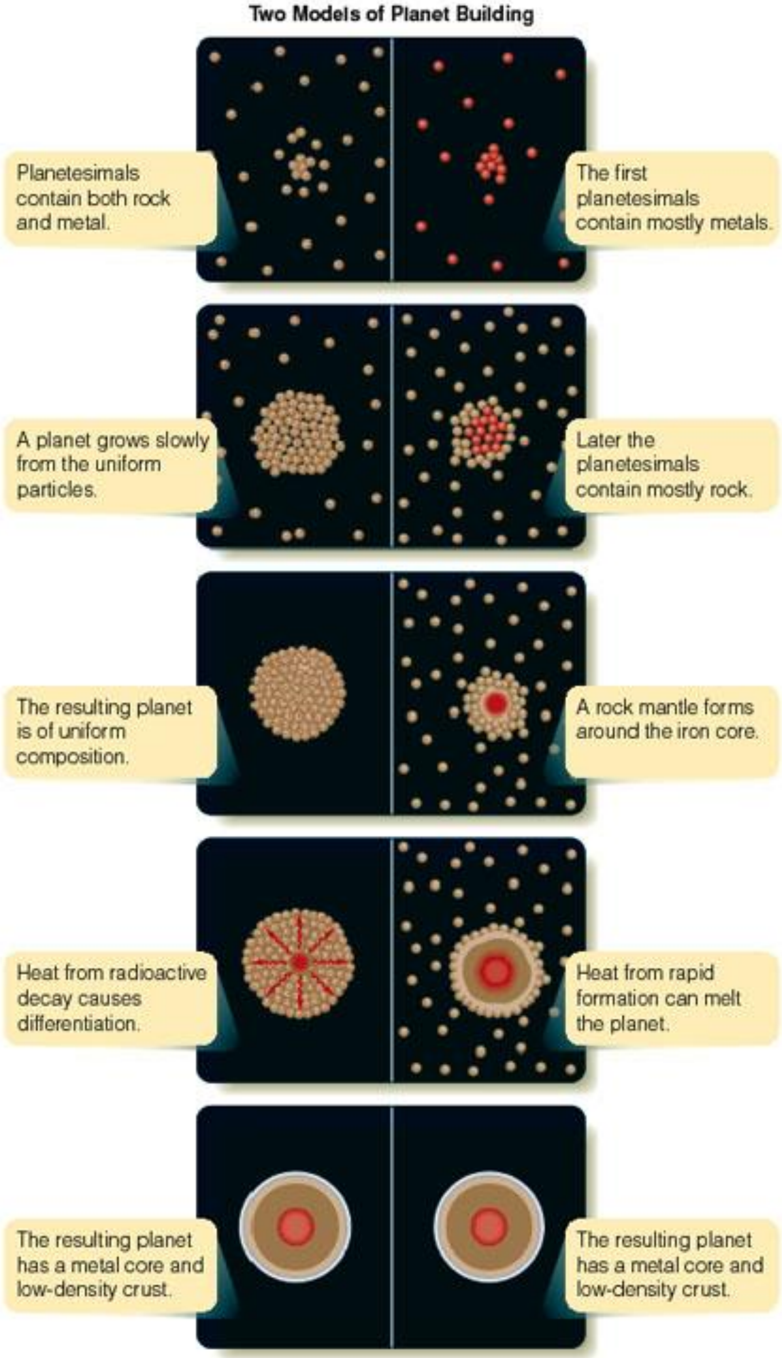
Only condensed materials could stick together to form planets

Condensation Sequence: Temperature in the protostellar cloud decreased outward

As protostellar cloud cools further out → metals with lower melting point condensed → change of chemical composition throughout solar system

Table 16-3 | The Condensation Sequence

Temperature (K)	Condensate	Planet (Estimated Temperature of Formation; K)
1500	Metal oxides	Mercury (1400)
1300	Metallic iron and nickel	
1200	Silicates	
1000	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)



The Growth of Protoplanets

Simplest form of planet growth:

Unchanged composition of accreted matter over time

As rocks melted, heavier elements sink to the center
→ chemical differentiation

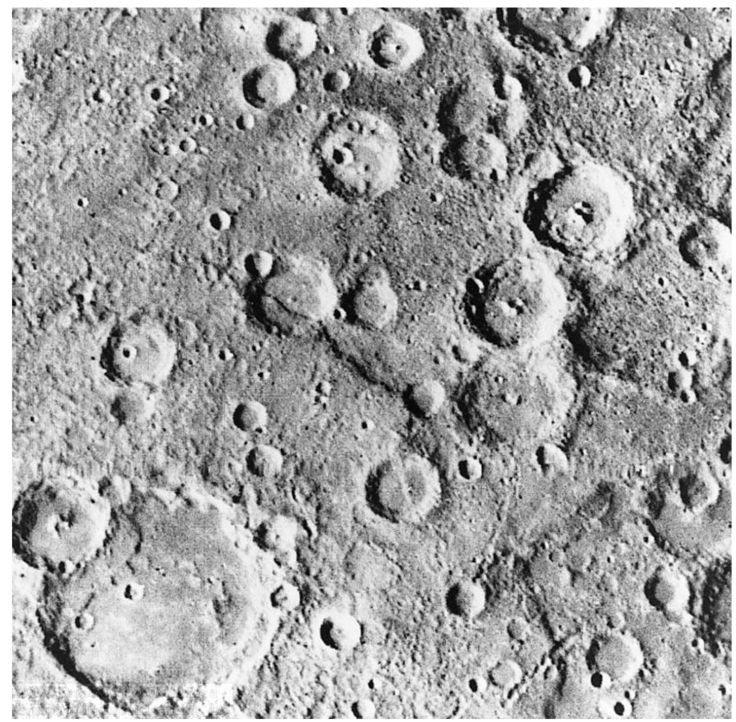
This also produces a secondary atmosphere
→ outgassing

Gradual change of grain composition due to cooling of nebula and storing of heat from potential energy

Clearing the Nebula

Remains of the protostellar nebula were cleared away by:

- Radiation pressure of the sun
- Solar wind
- Sweeping-up of space debris by planets



Surfaces of the moon and Mercury show evidence for heavy bombardment by asteroids

The Jovian Problem

Two problems for the theory of planet formation:

1) Observations of extrasolar planets indicate that Jovian planets are common.

2) Protoplanetary disks tend to be evaporated quickly (typically within ~ 100,000 years) by the radiation of nearby massive stars.

→ Too short for Jovian planets to grow!

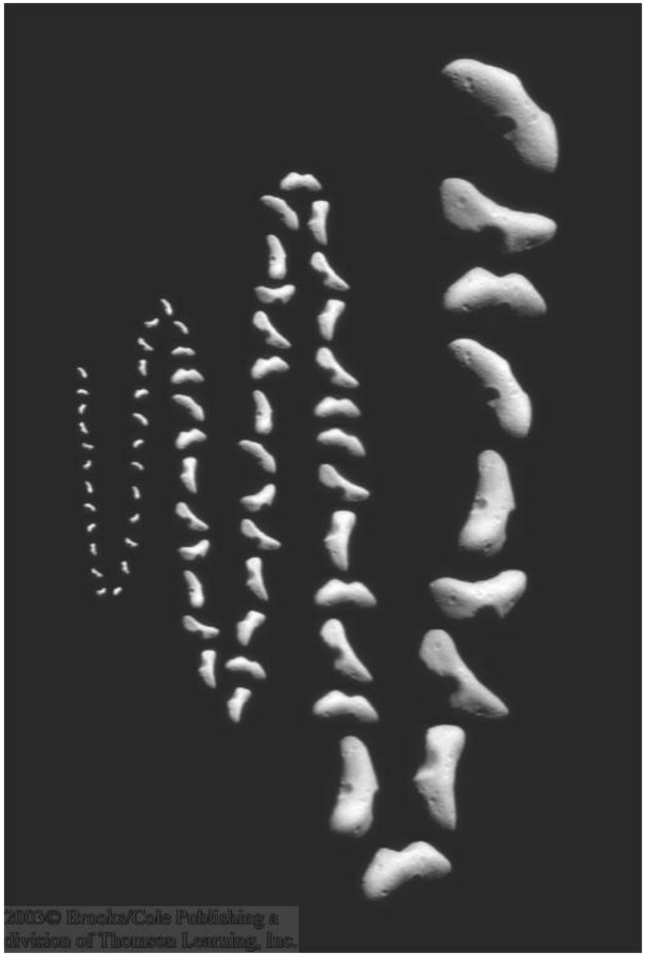
Solution:

Computer simulations show that Jovian planets can grow by direct gas accretion without forming rocky planetesimals.

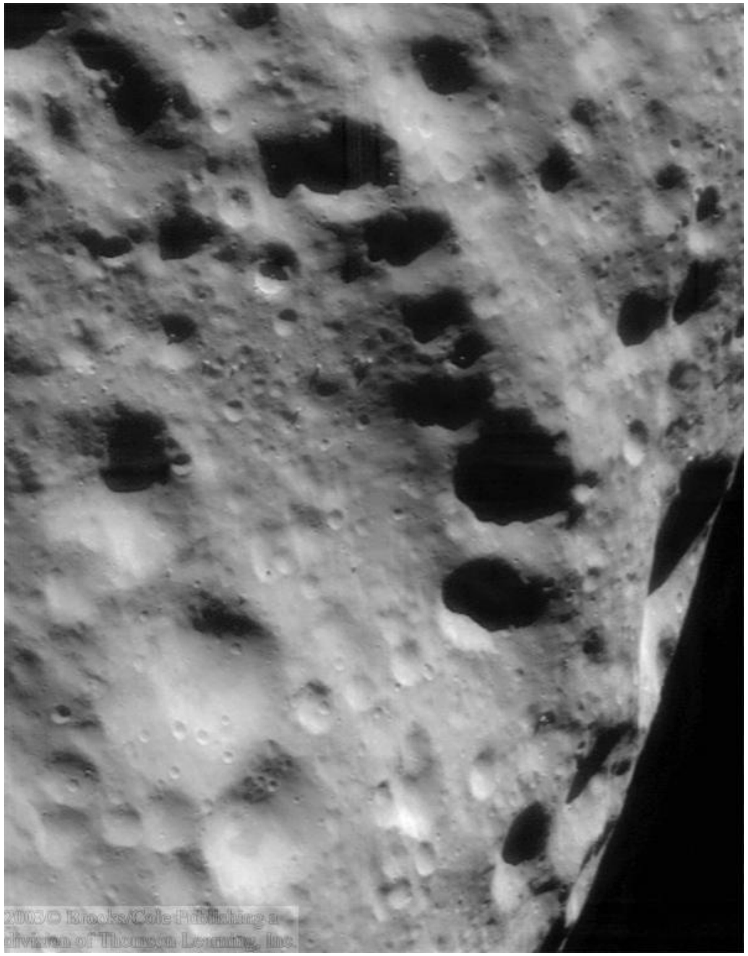
Space Debris

In addition to planets, small bodies orbit the sun:

Asteroids, comets, meteoroids



Asteroid Eros, imaged by the NEAR spacecraft

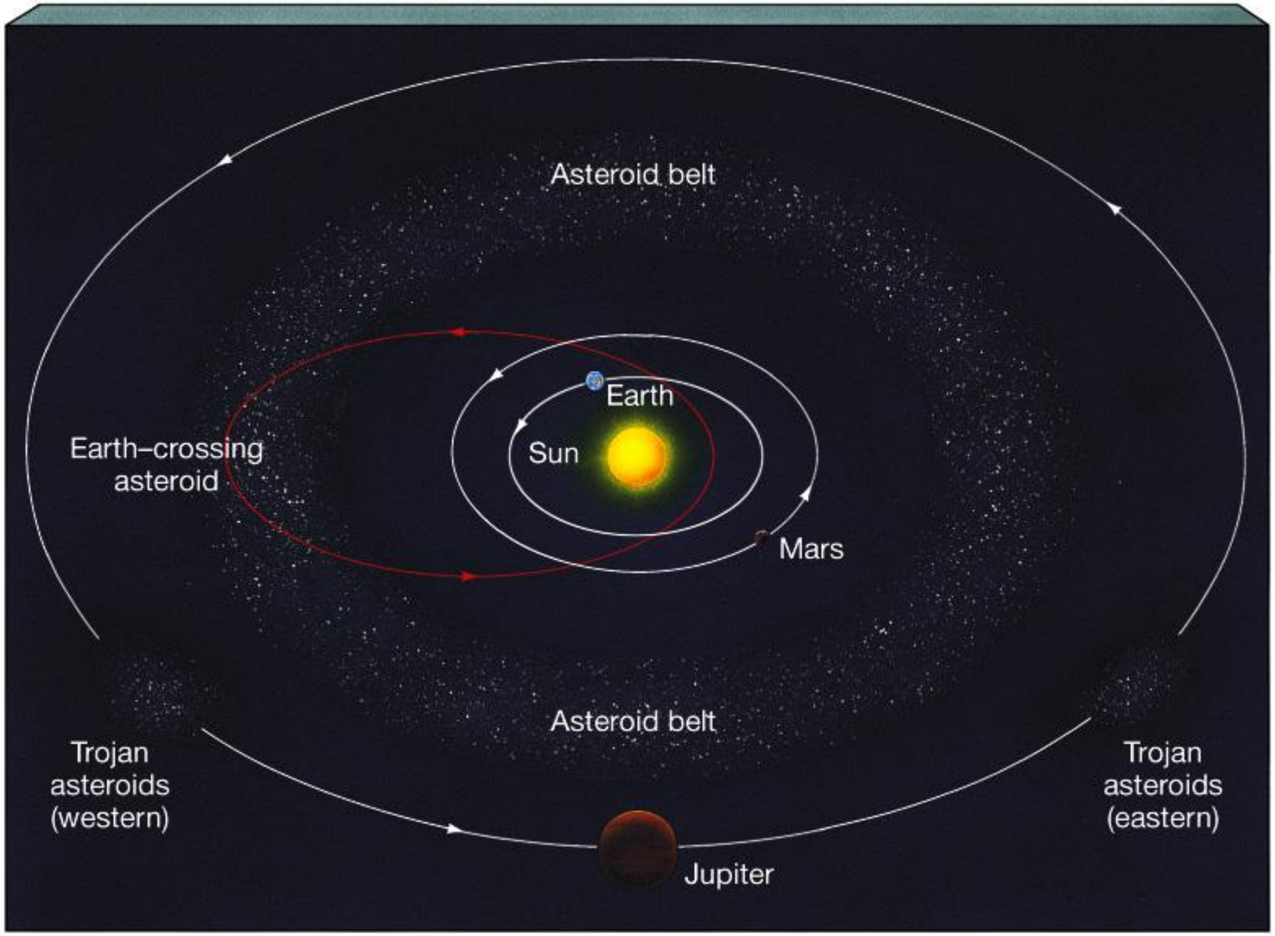


Asteroids

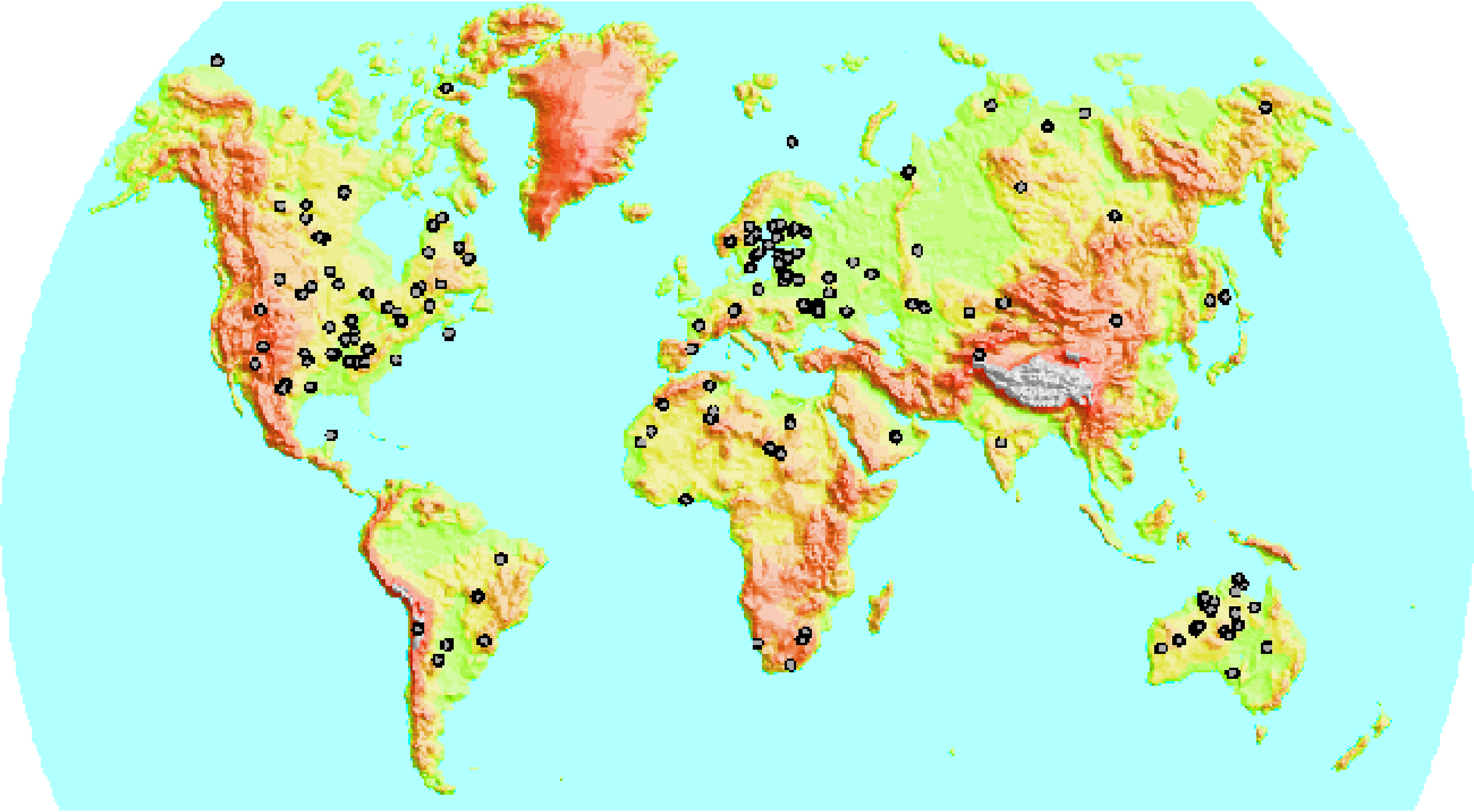
Most asteroids remain in the Asteroid belt between Mars and Jupiter but a few have orbits that cross Earth's path

Rocks with sizes greater than 100 m across

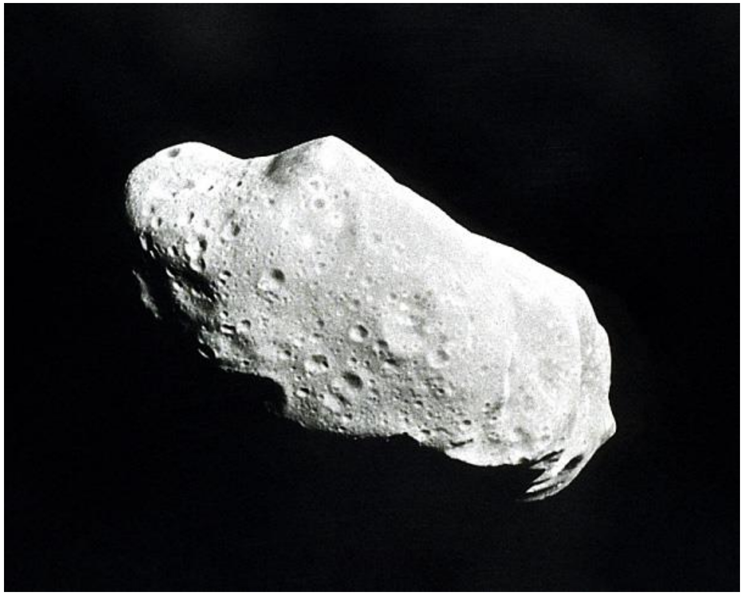
Three asteroids hit the Earth every 1 million years!



Known asteroid impact sites



Asteroid sizes range from 100m to about 1000km

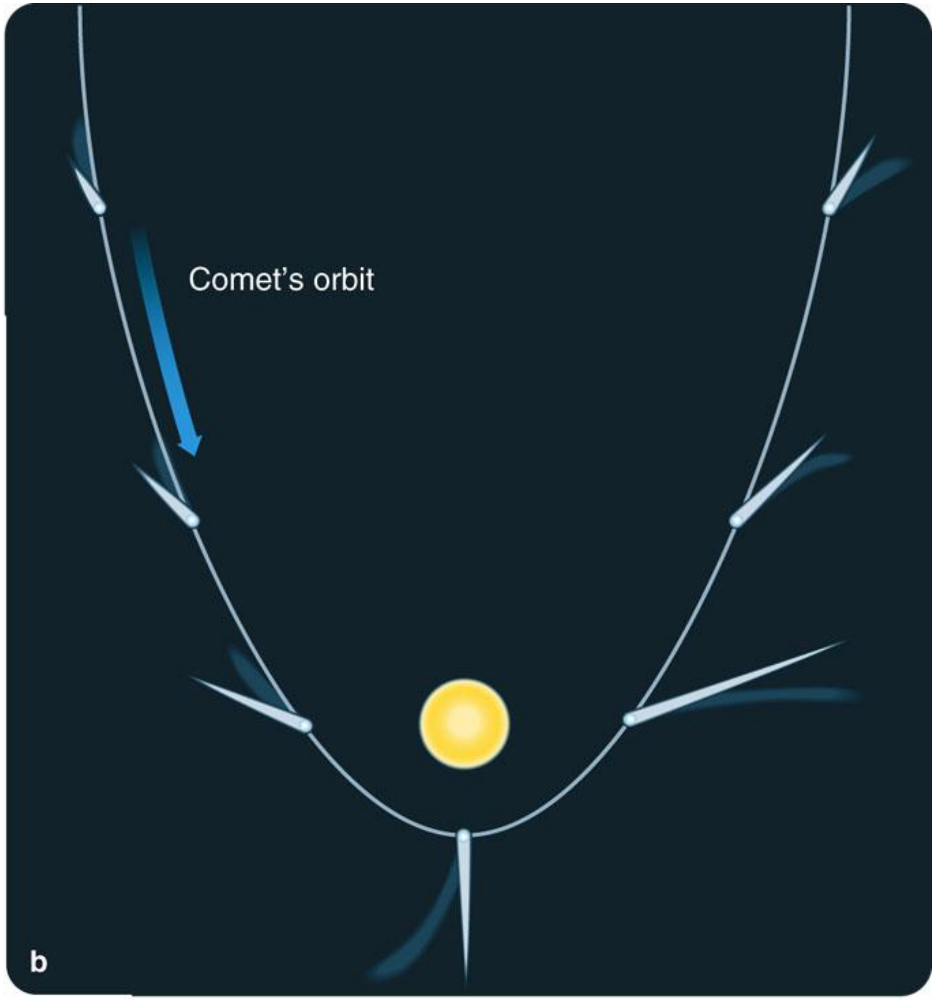


They are composed of carbon or iron and other rocky material

The Asteroid belt is a group of rocks that appear to have never joined to make a planet. Why?

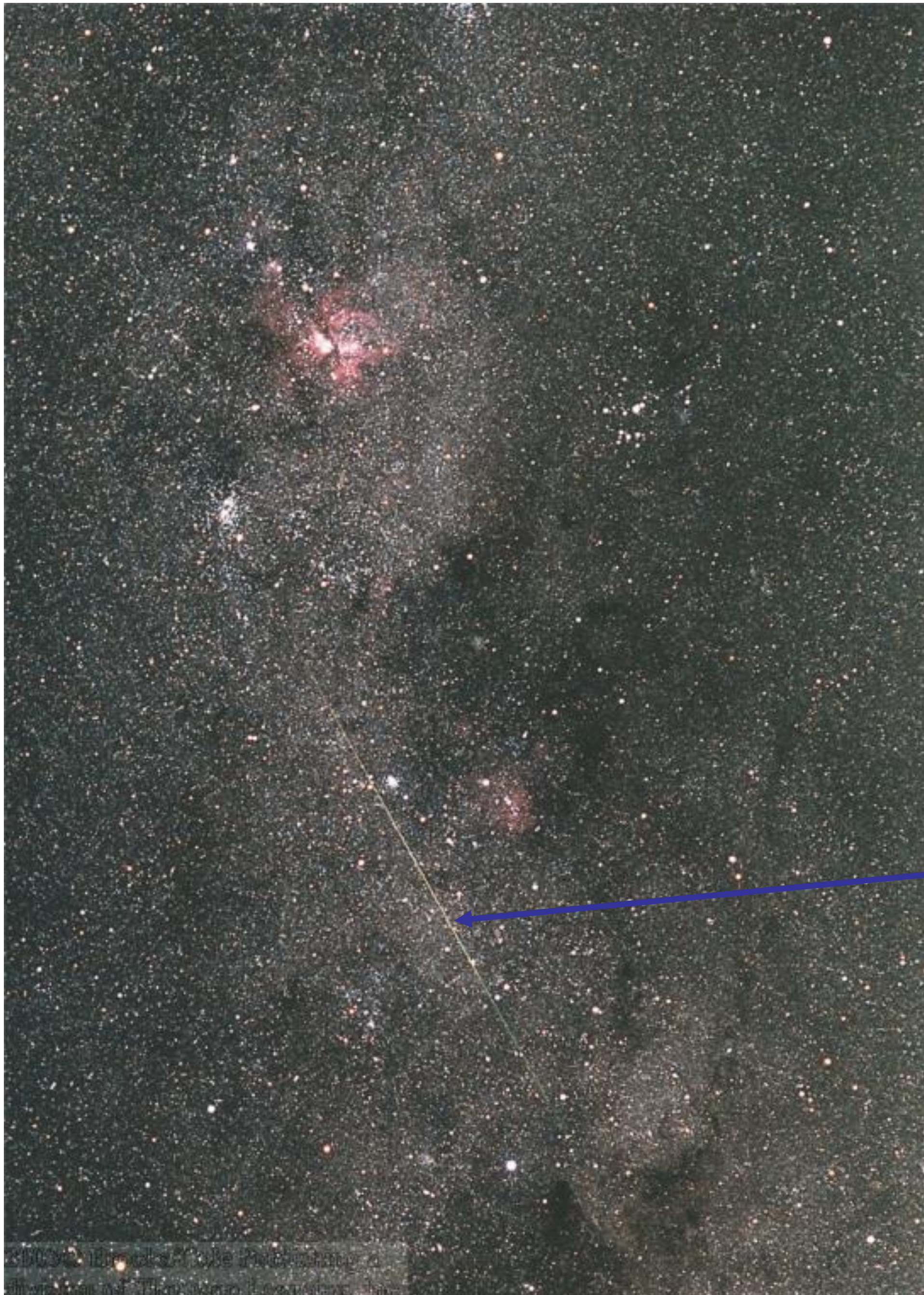
- Too little mass to be a planet
- Asteroids have different chemical compositions

Comets



Icy nucleus, which evaporates and gets blown into space by solar wind pressure.

Mostly objects in highly elliptical orbits, occasionally coming close to the sun.



Meteoroids

Small (μm – mm sized) dust grains throughout the solar system

If they collide with Earth, they evaporate in the atmosphere.

→ Visible as streaks of light: meteors,

if it makes it to the ground, it is a meteorite

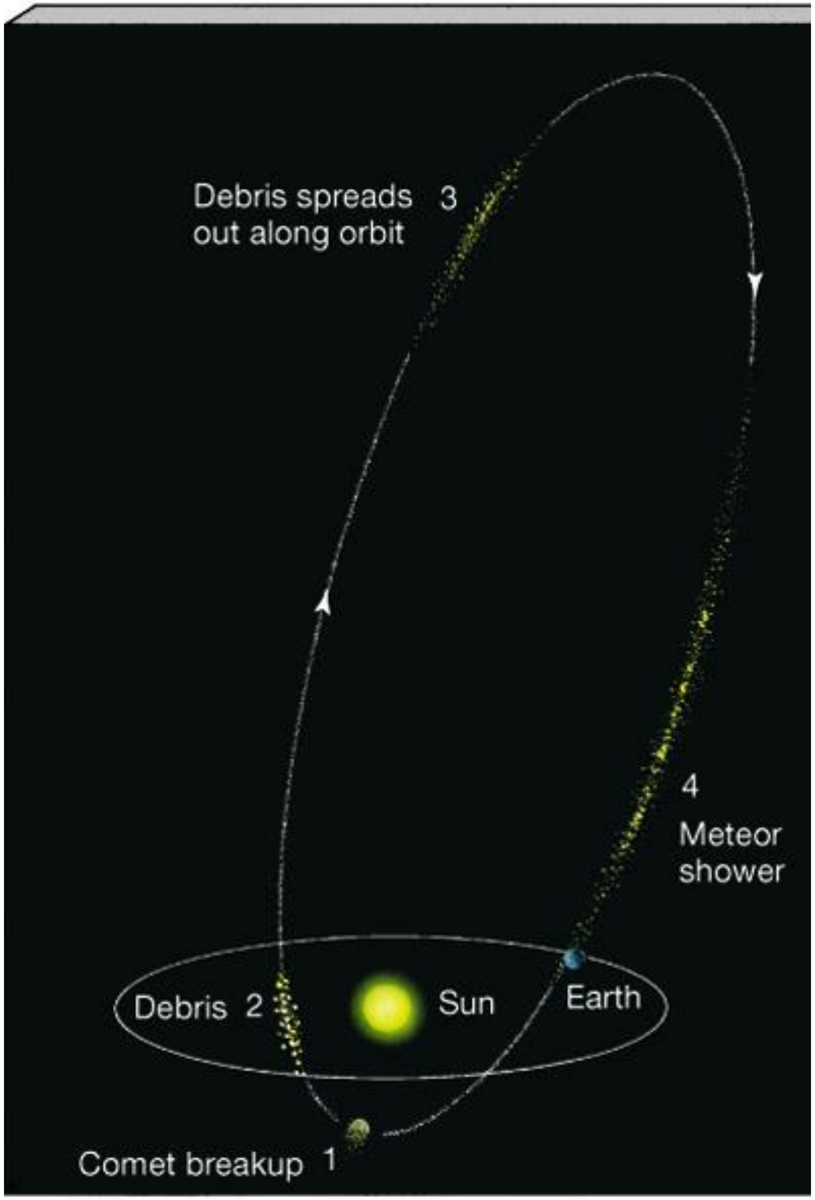
Meteoroids

- interplanetary rocky material smaller than 100m (down to grain size)

• called a meteor as it burns in the Earth's atmosphere

• if it makes it to the ground, it is a meteorite

Most meteor showers are the result of the Earth passing through the orbit of a comet which has left debris along its path

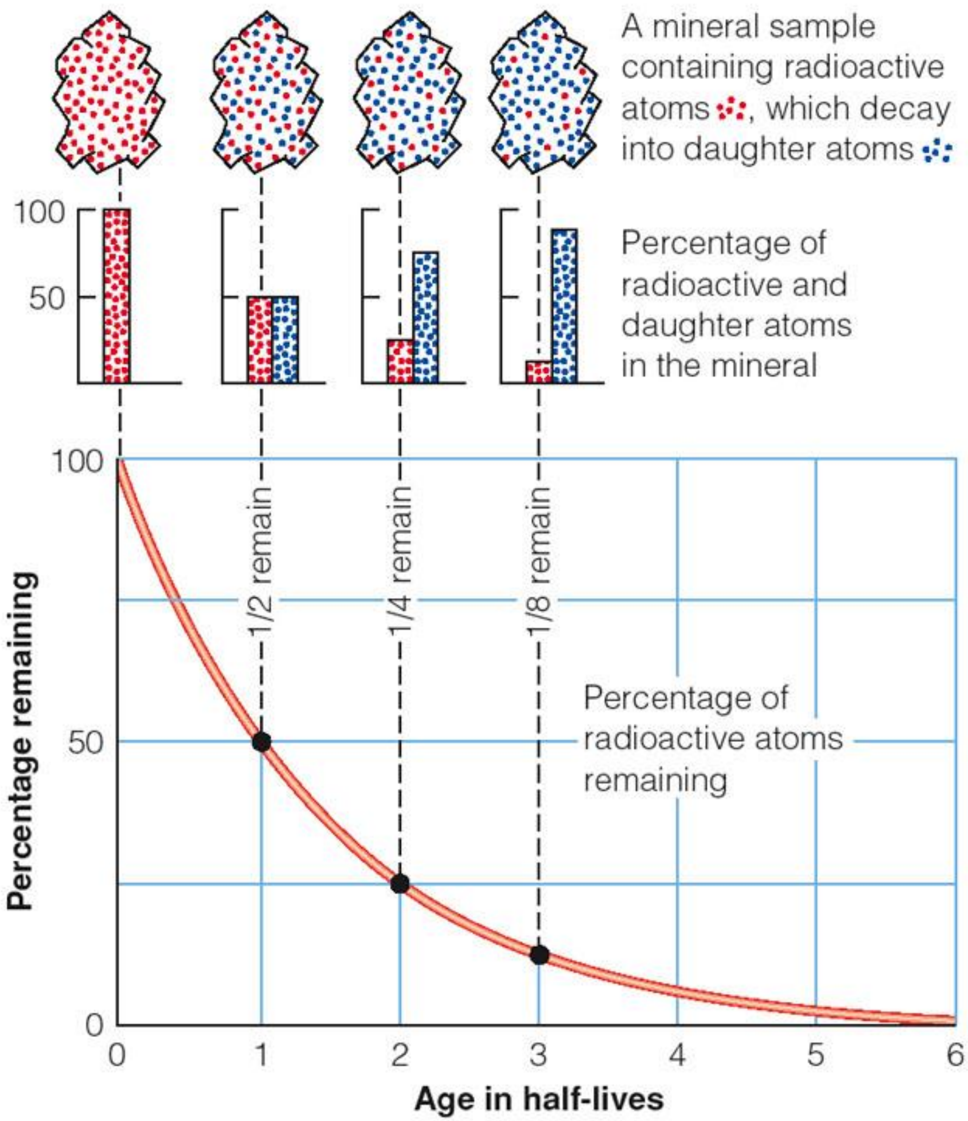


Meteorites are rocky - mainly iron and nickel
Some contain carbonaceous material - rich in organic material

Meteor crater near Winslow, Arizona - the culprit was probably 50 m across weighing 200,000 tons!

Meteor showers:
Orionid – Oct 21/22
Leonid – Nov 18/19
Geminid – Dec 14/15

The Age of the Solar System



Sun and planets should have about the same age.

Ages of rocks can be measured through radioactive dating:

Measure abundance of a radioactively decaying element to find the time since formation of the rock.

Dating of rocks on Earth, on the moon, and meteorites all give ages of ~ 4.6 billion years.