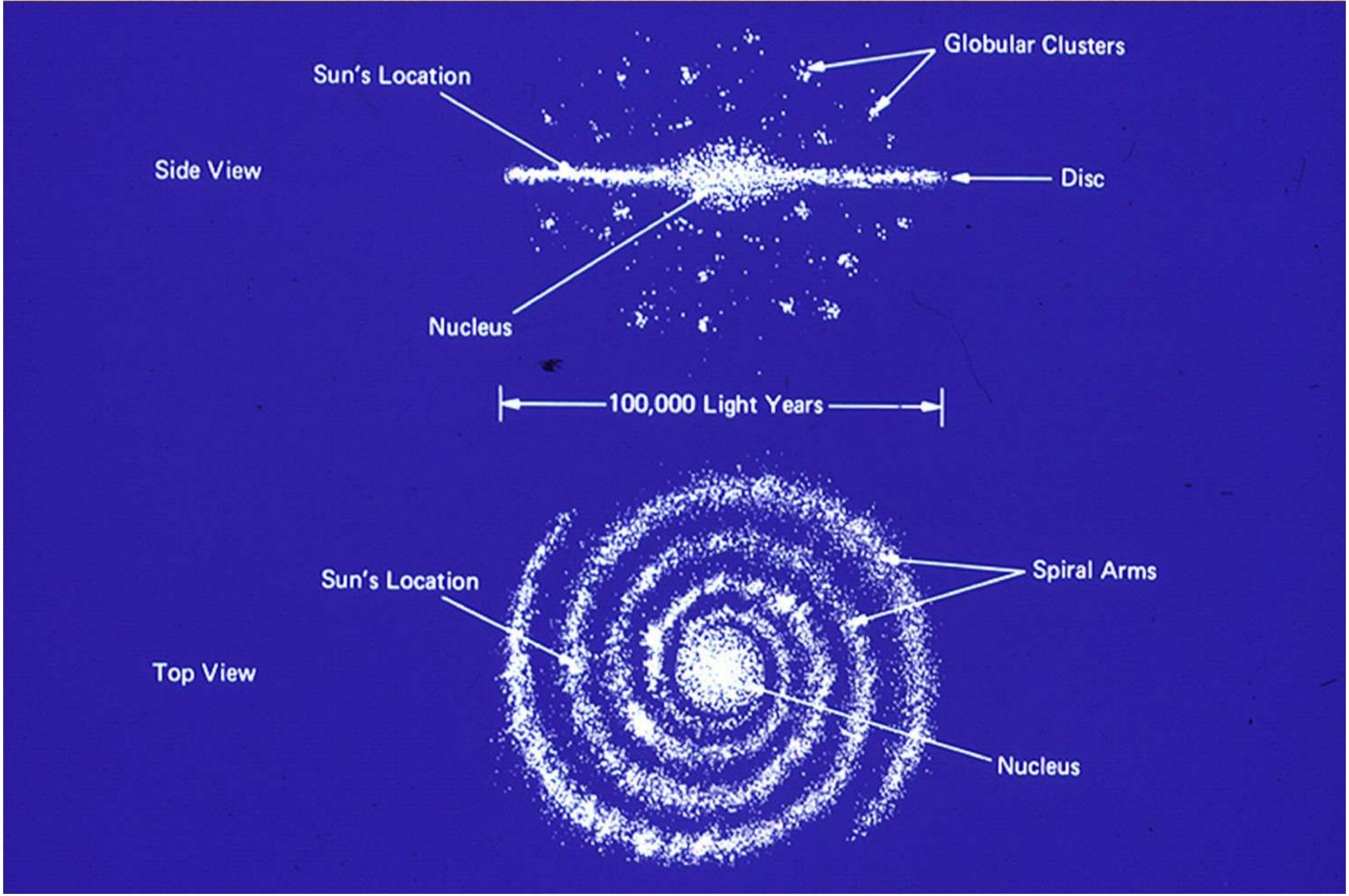
The origin of the Solar System

Our galaxy, the Milky Way



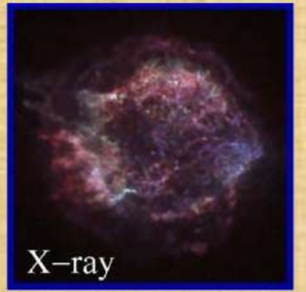
When Did the Solar System Form?

Å 4.56 billion years ago

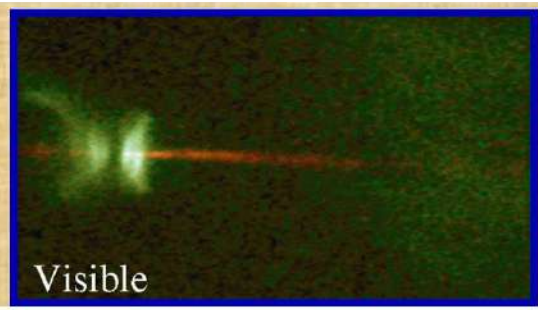
Å How do we know? (evidence for formation)

- ÅLunar samples - 4.5 to 4.6 Ga
- ÅMeteorites - 4.56 Ga
- ÅEarth ï 3.9 (or 4.4 Ga)

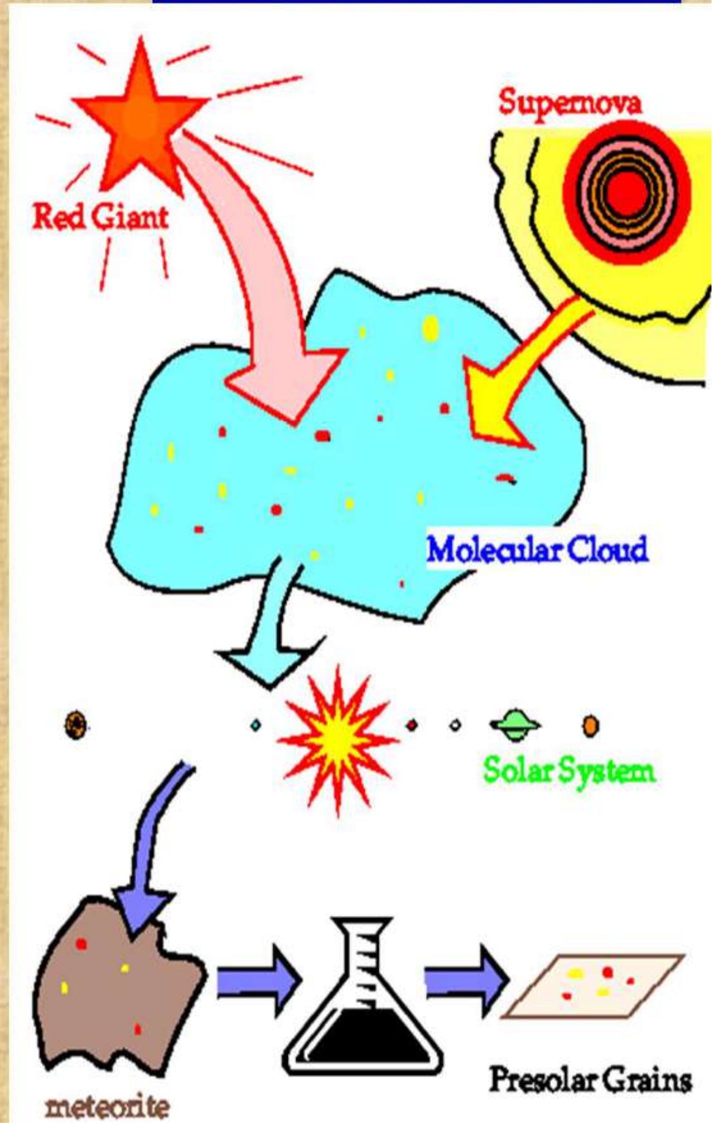
Old Historical thoughts about the formation of Solar System and Universe



"The Big Picture"



- The "Big Bang", the birth of the Universe ~ 13 Gy ago, produced H and He. These elements formed stars which cluster in galaxies with billions of stars; our galaxy, the Milky Way, formed ~ 10 Gy ago.
- Other elements are synthesized in the interiors of stars such as Red Giants and Supernovae.
- Upon ejection into interstellar space from dying stars, some elements condense into dust grains (presolar grains) and amorphous dust, either in stellar atmospheres or in interstellar space.
- Gas and dust collect into giant, cold molecular clouds.
- Dense cores collapse into stars, such as the Sun 4.56 Gy ago and planets, asteroids and comets form.
- Asteroids collide and fragments fall on Earth as meteorites
- We study meteorites and the presolar grains.



Sun-planet distance (relative to Earth: AU)

Mercury	0.4 AU
Venus	0.7
Earth	1.0
Mars	1.5
Jupiter	5.2
Saturn	9.5
Uranus	19
Neptune	30

1 AU = 150 million km

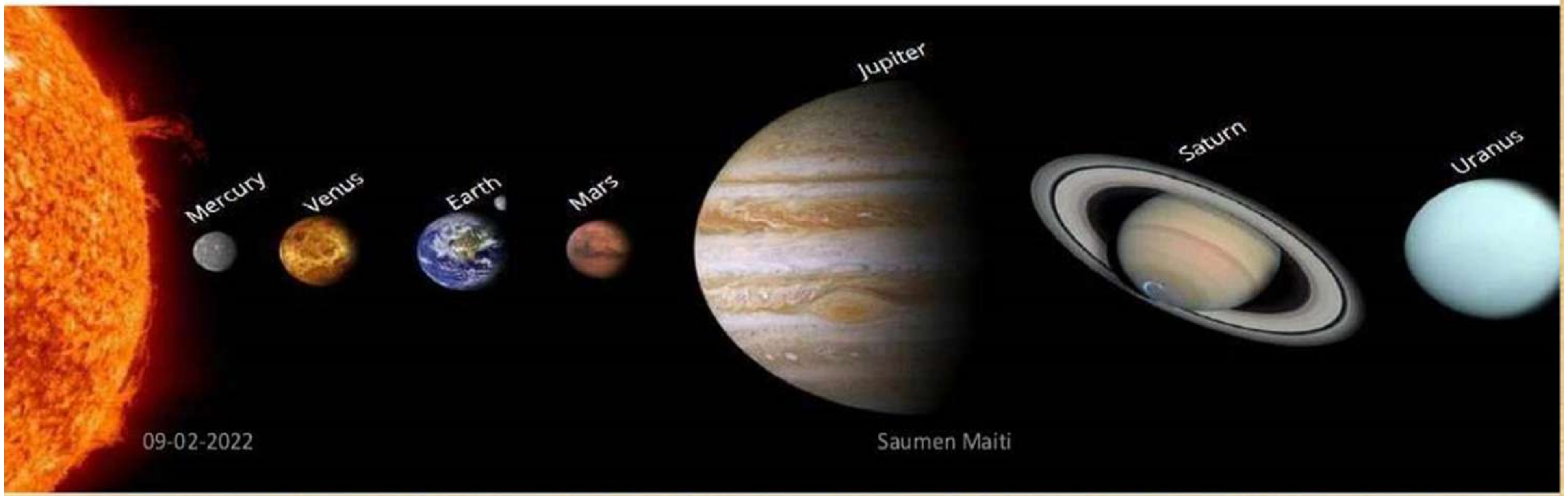
Bode's law

- In 1772 the German astronomer Johann Bode devised an empirical formula to express the approxim
planets from the Sun.
- A series of numbers is created in the following way: the first number is zero, the second is 0.3, and
by doubling the previous number.
- This gives the sequence 0, 0.3, 0.6, 1.2, 2.4, 4.8, 9.6, 19.2, 38.4, 76.8, etc.
- Each number is then augmented by 0.4 to give the sequence: 0.4, 0.7, 1.0, 1.6, 2.8, 5.2, 10.0, 19.6,
series can be expressed mathematically as follows:

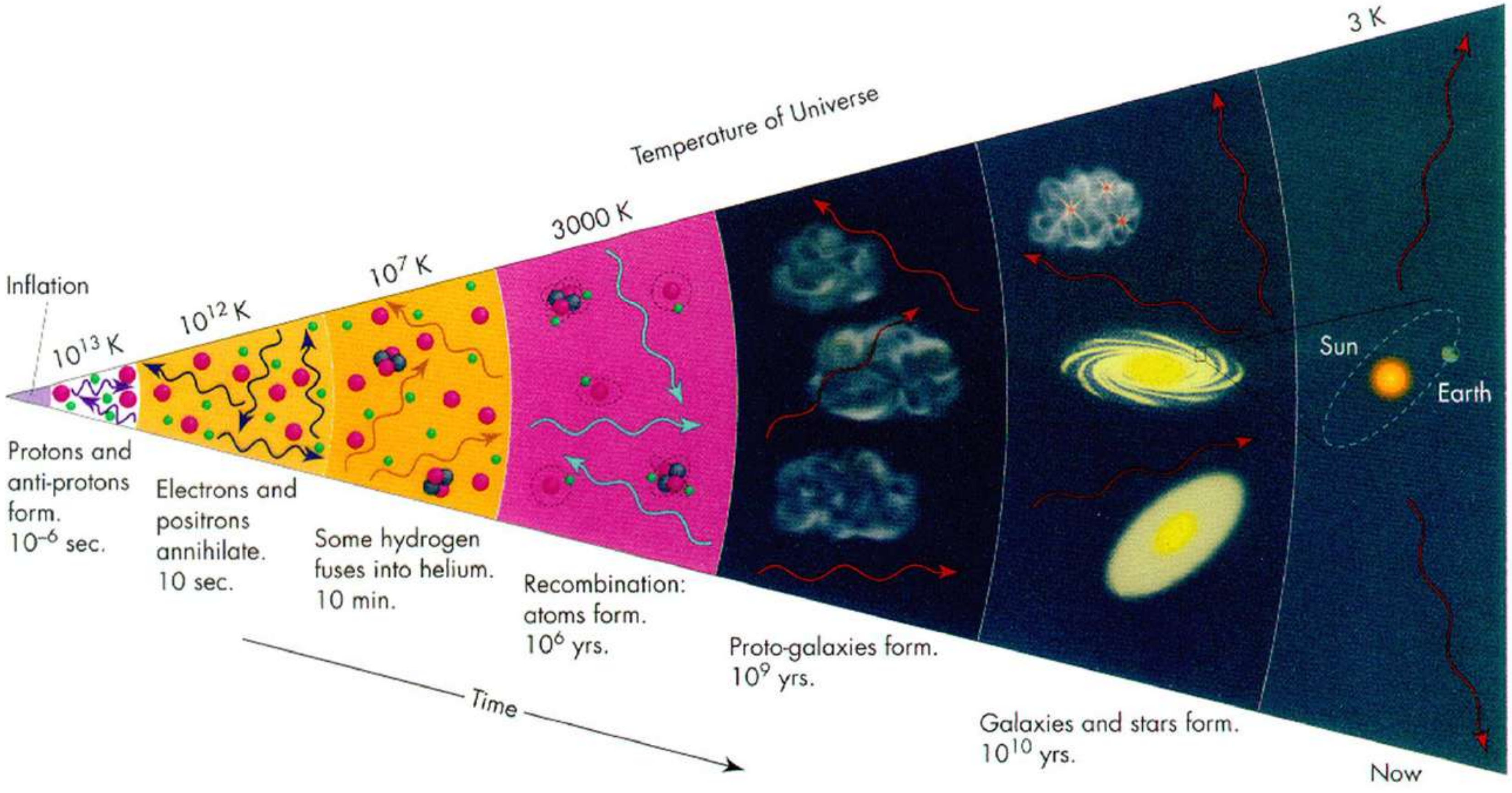
$$d_n = 0.4 \quad \text{for } n = 1$$

$$d_n = 0.4 + 0.3 \times 2^{n-2} \quad \text{for } n \geq 2$$

- This expression gives the distance d_n in astronomical units (AU) of the nth planet from the Sun. It



Formation of the Universe



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)

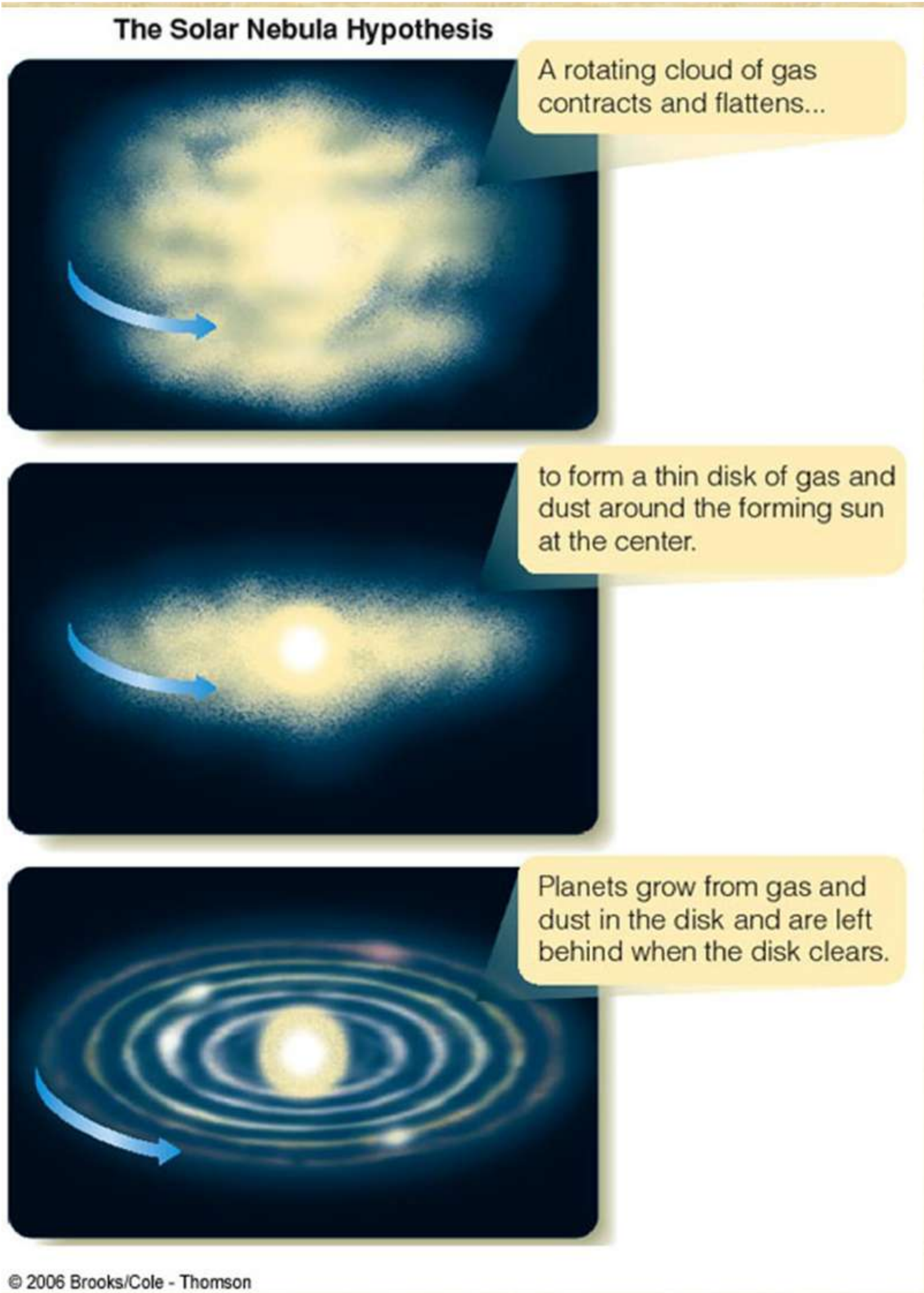
Catastrophic hypotheses predict: Only few stars should have planets!

2) Evolutionary hypotheses

Example: Laplaceõs nebular hypothesis:

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

Evolutionary hypotheses predict: Most stars should have planets!



The Solar Nebula Hypothesis

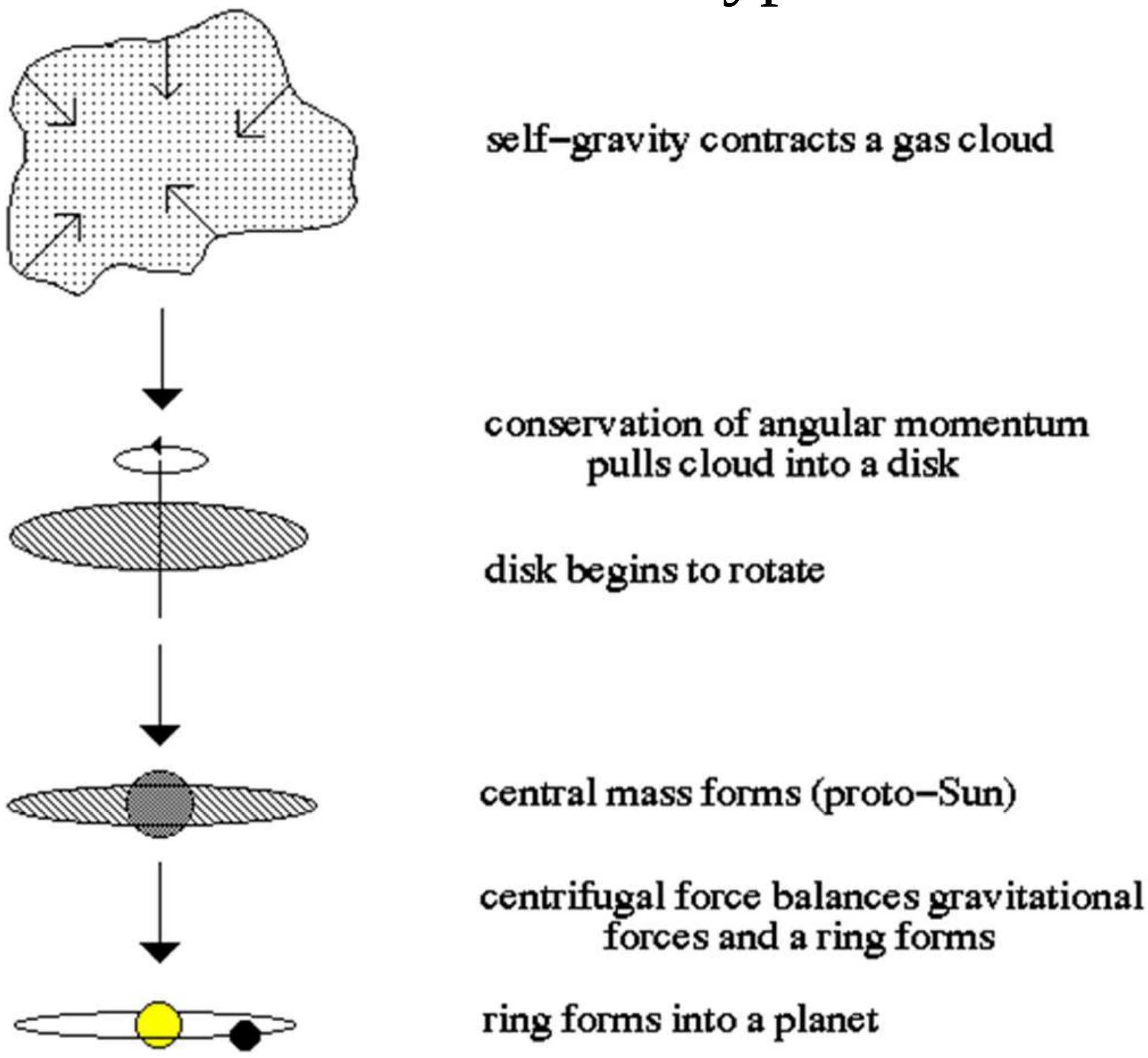
Basis of modern theory of planet formation.

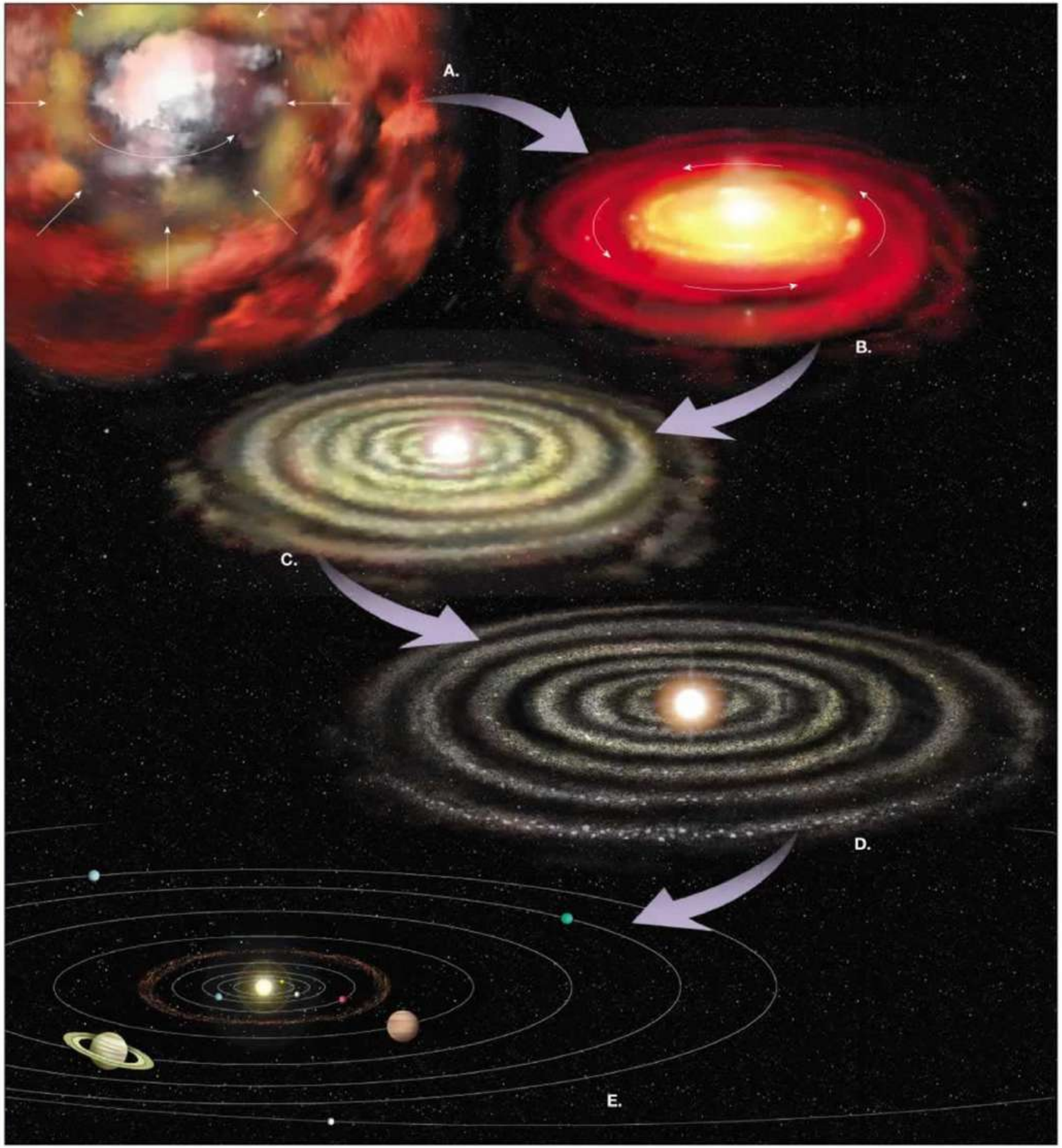
Planets form at the same time from the same cloud as the star.

Planet formation sites observed today as dust disks of T Tauri stars.

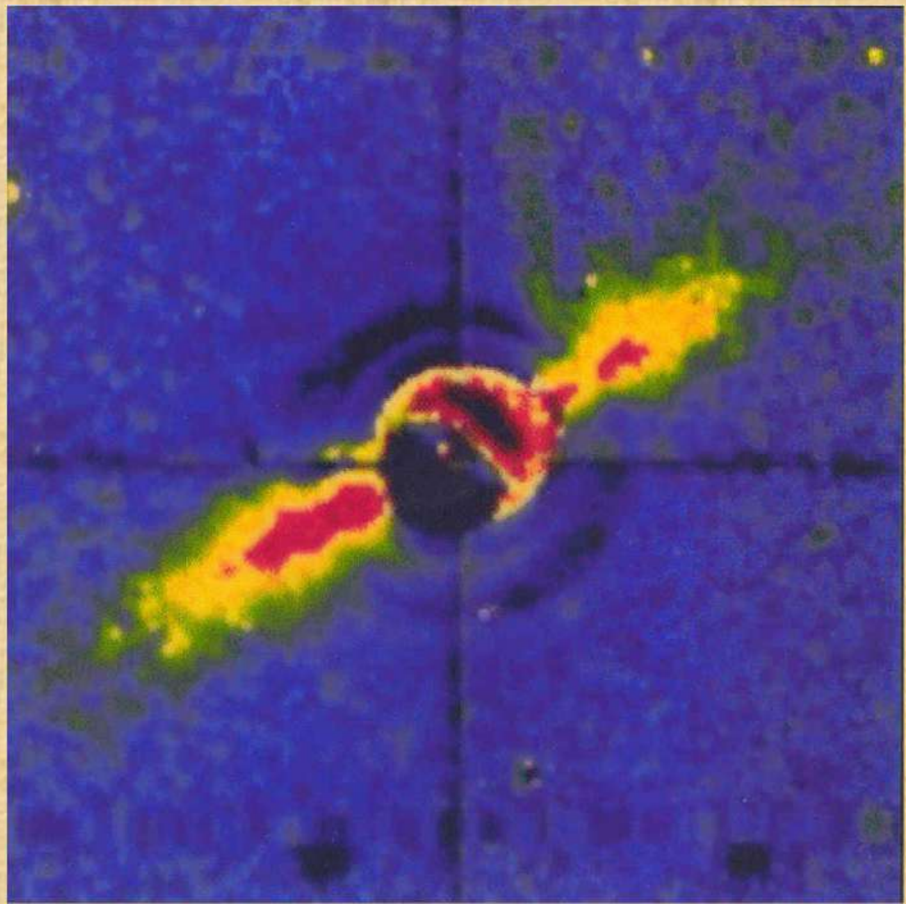
Sun and our solar system formed ~ 5 billion years ago.

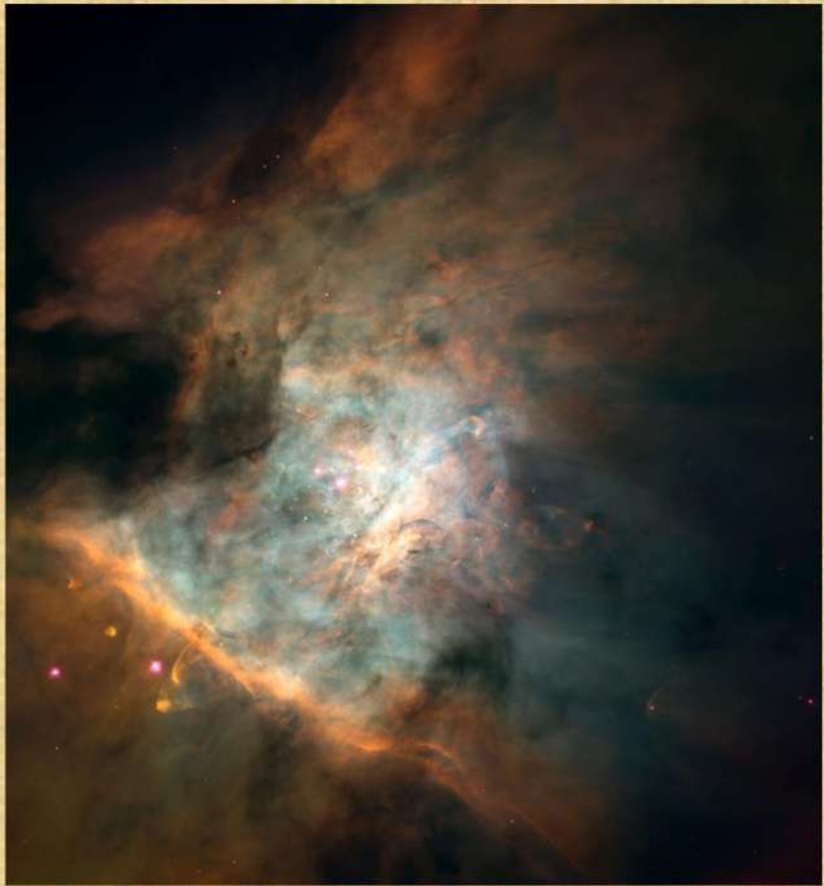
Nebular Hypothesis




A.
B.
C.
D.
E.

Beta Pectoris dust disk





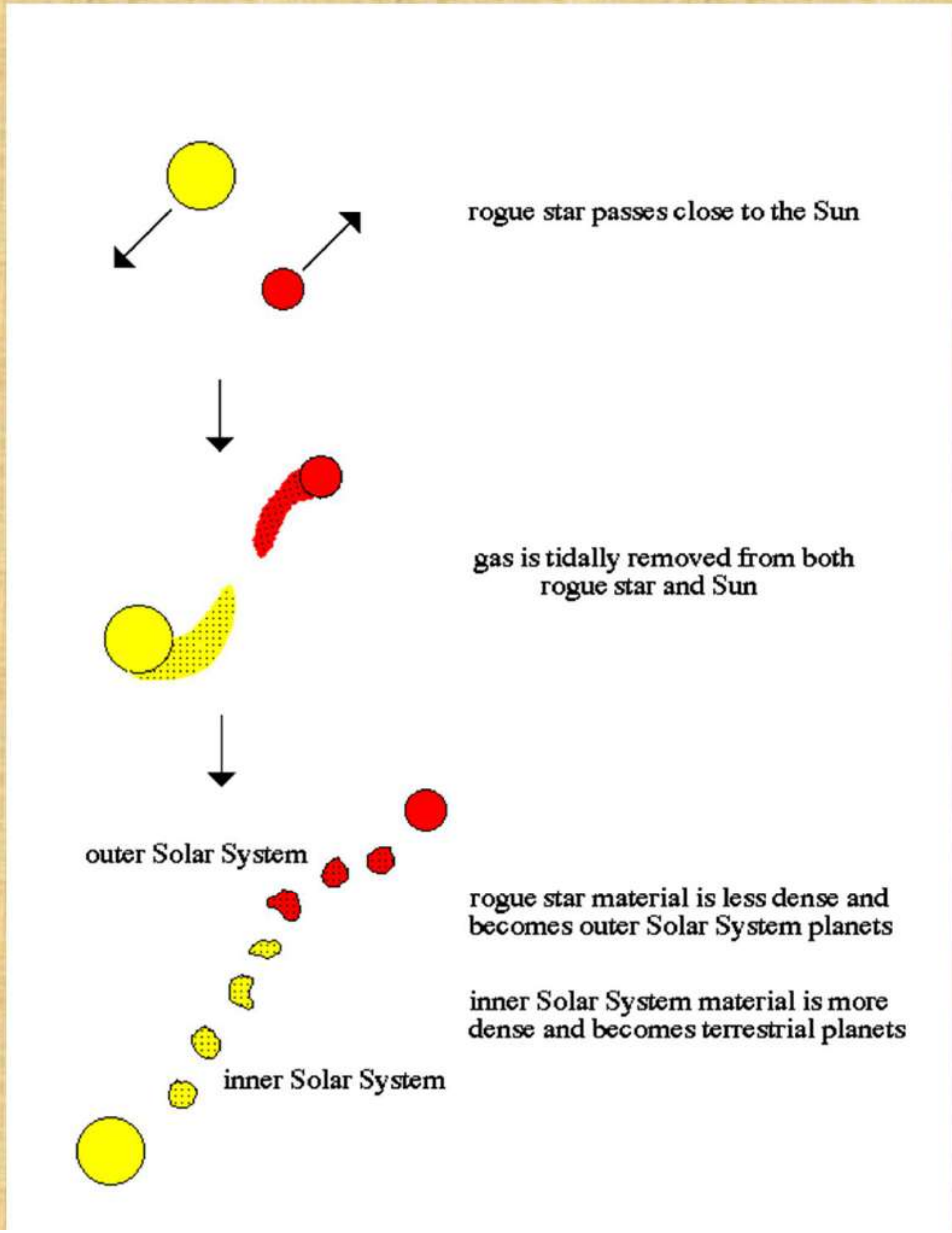
Orion Nebula, giant stellar nursery ~1600 light years away

At the heart of the Orion Nebula lies a complex of molecular clouds where abundant star formation is occurring today.

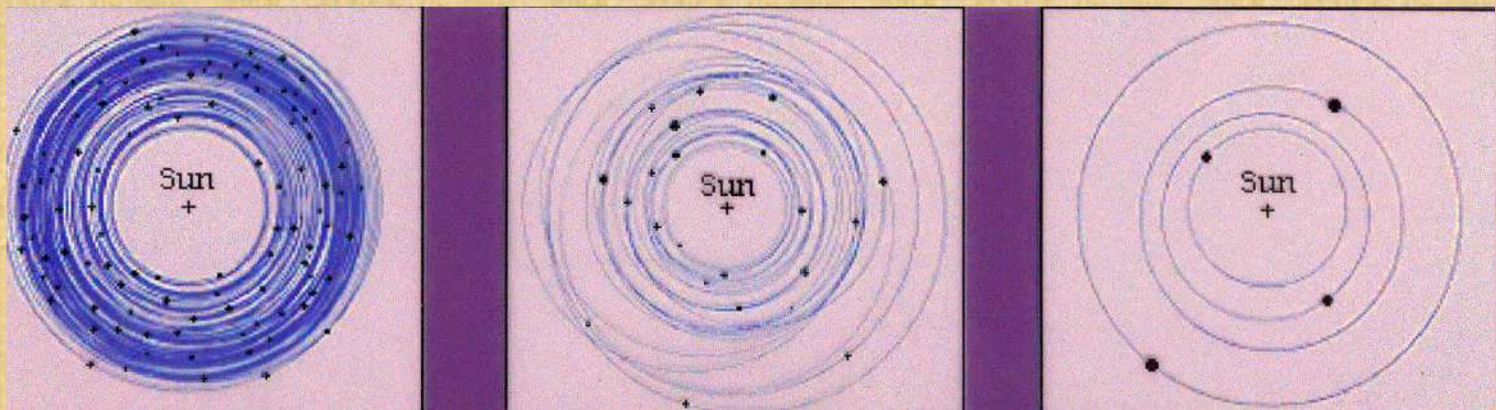
The clouds are illuminated by a flood of ultraviolet light emitted by four bright stars, collectively called the Trapezium.

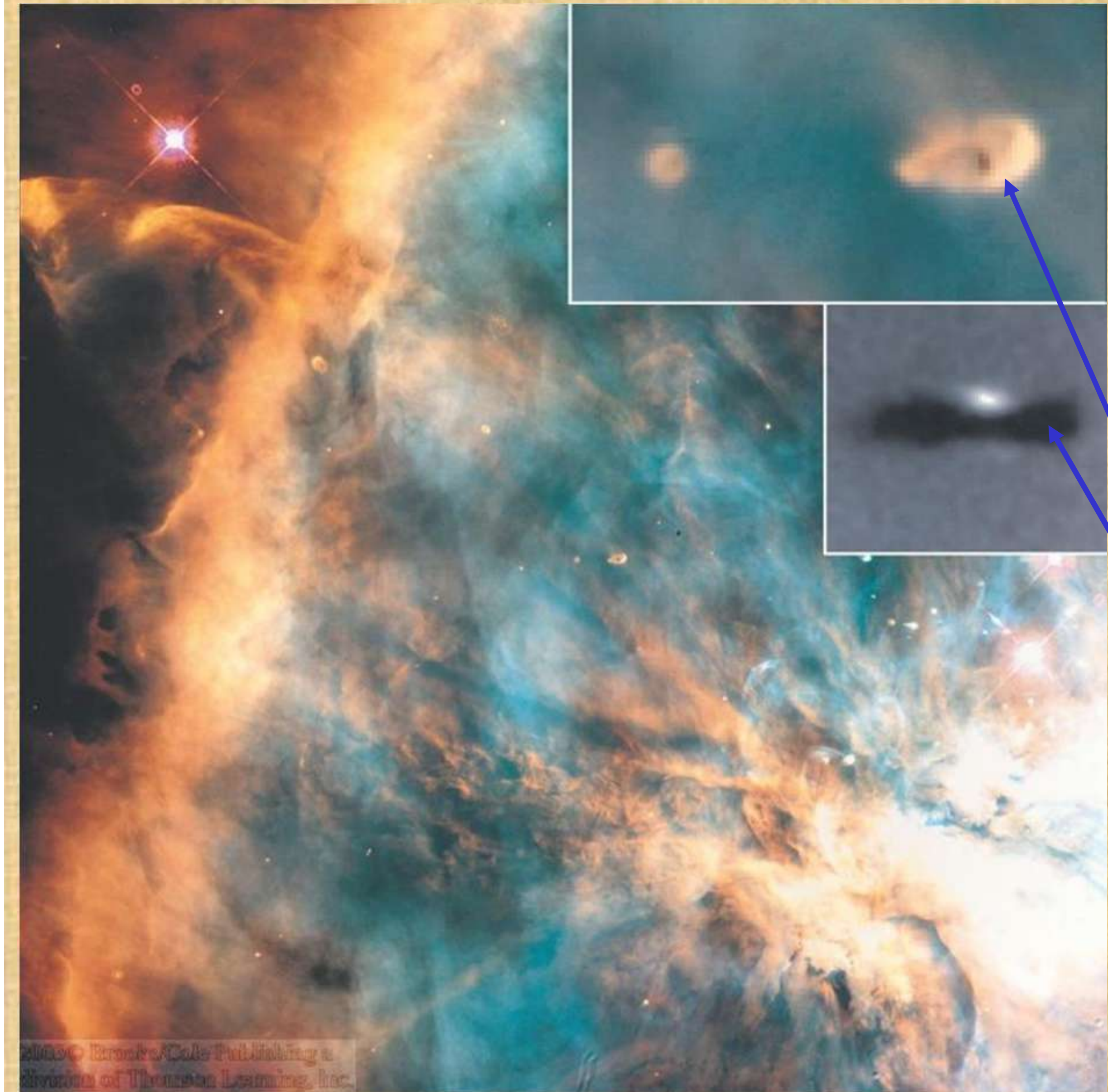
More than 150 protoplanetary disks have been found in this mosaic of HST images.

Dualistic Hypothesis



Planetesimals forming planets

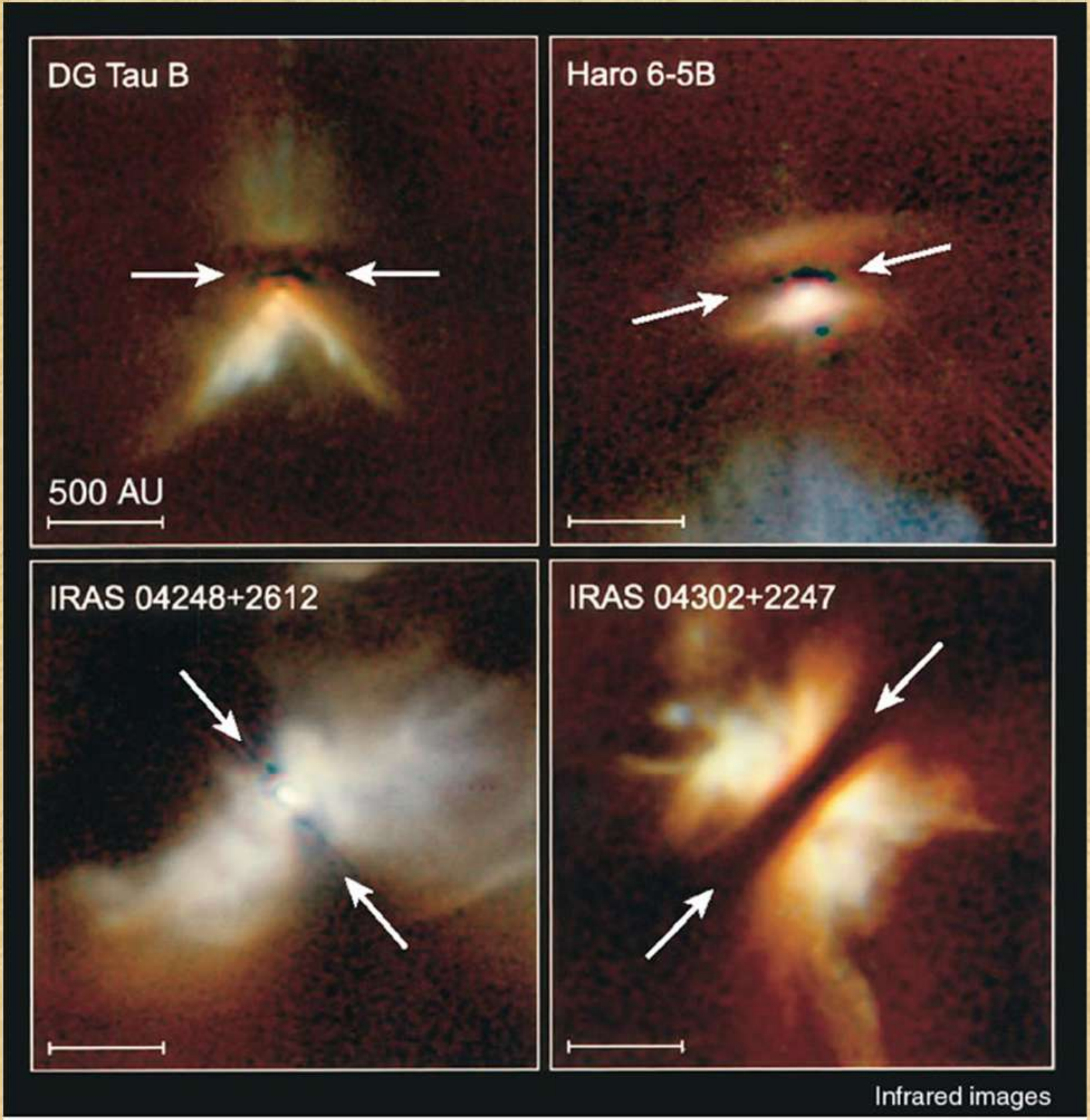




Evidence for Ongoing Planet Formation

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

Probably sites of planet formation right now!



Dust Disks around Forming Stars

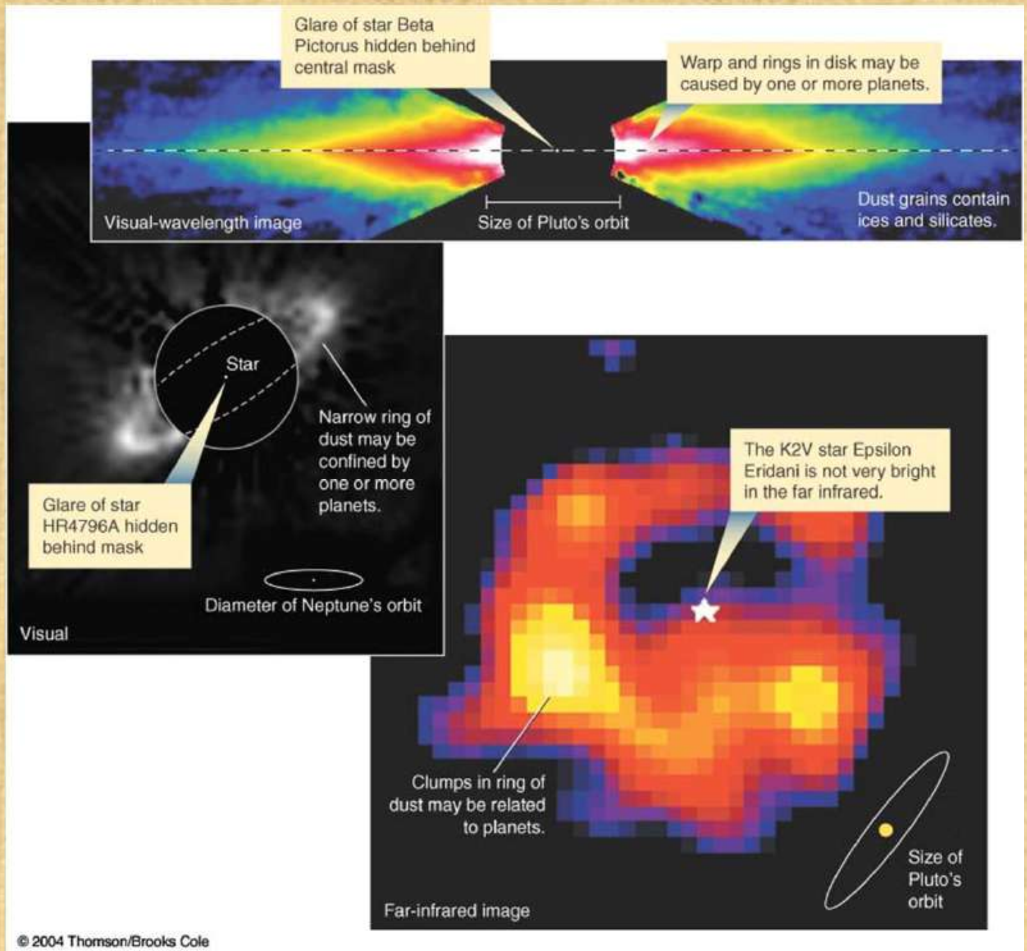
Dust disks around some T Tauri stars can be imaged directly (HST).

Extrasolar Planets

Modern theory of planet formation is evolutionary

→ Many stars should have planets!

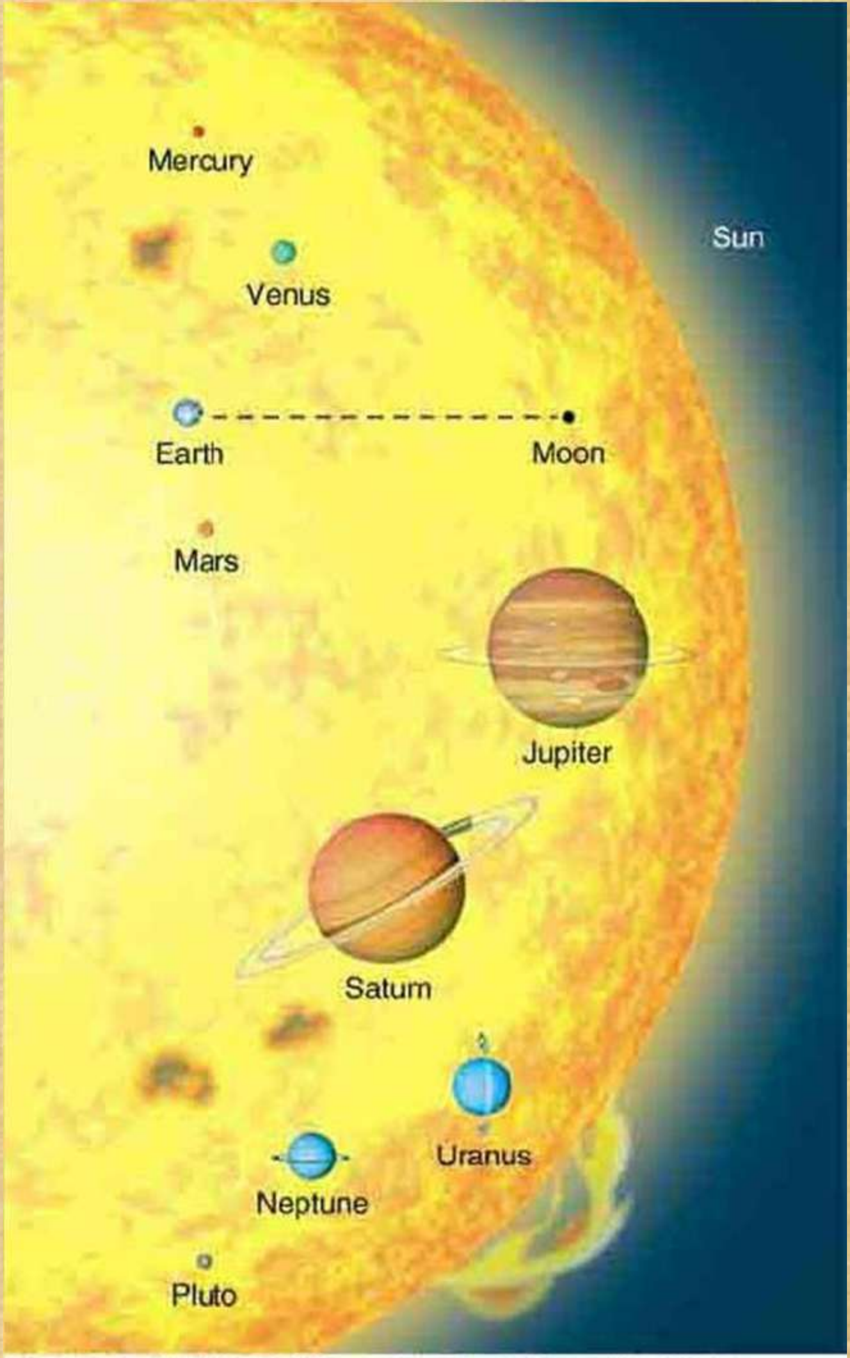
→ planets orbiting around other stars = ñExtrasolar planetsò



Extrasolar planets can not be imaged directly.

Detection using same methods as in binary star systems:

Look for ñwobblingò motion of the star around the common center of mass.



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.

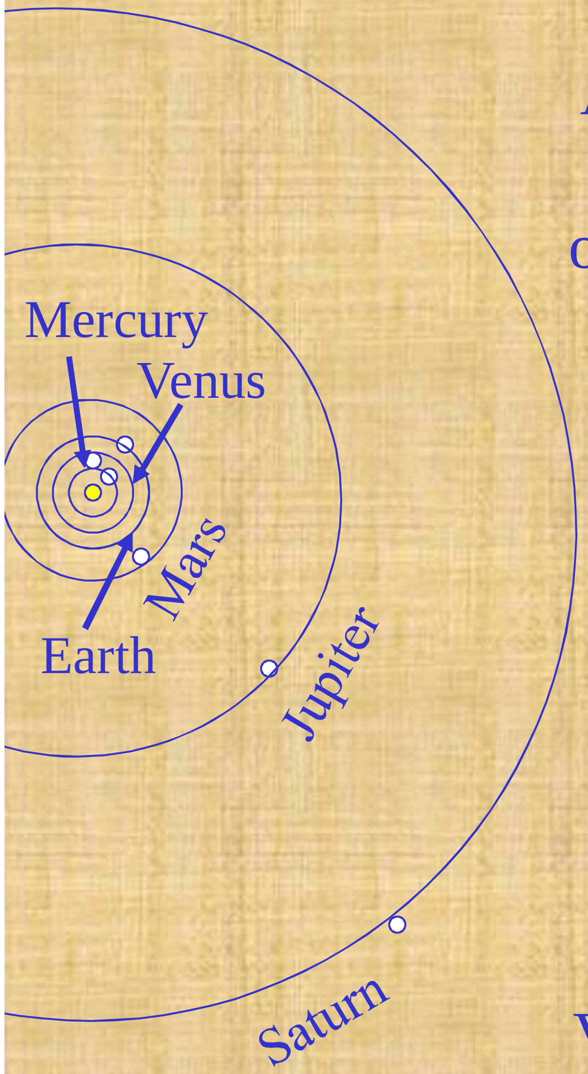
Jupiter: ~ size of an apple seed.

Saturn: ~ slightly smaller than Jupiterõs ñapple seedò.

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).

Orbits generally inclined by no more than 3.4^{o}

Exceptions:

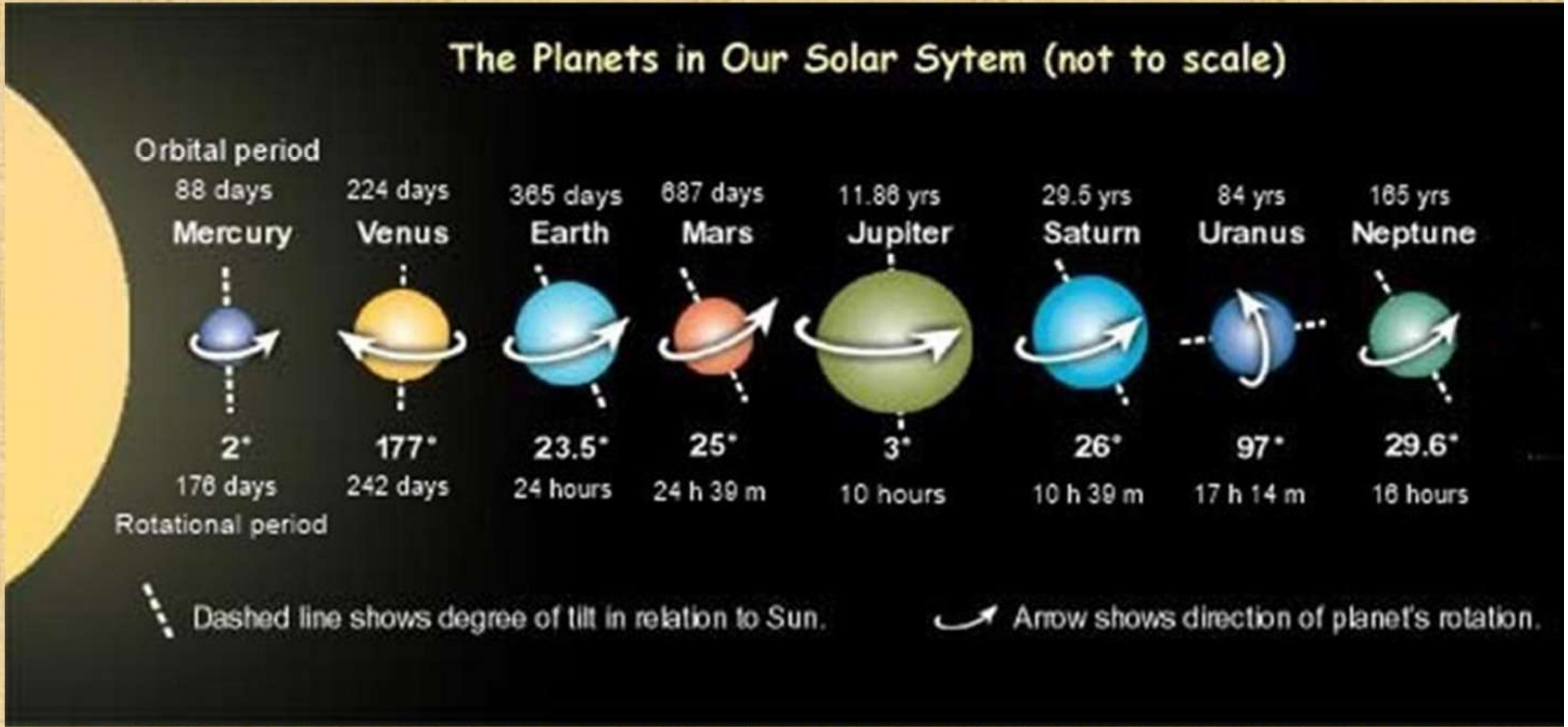
Mercury (7^{o})

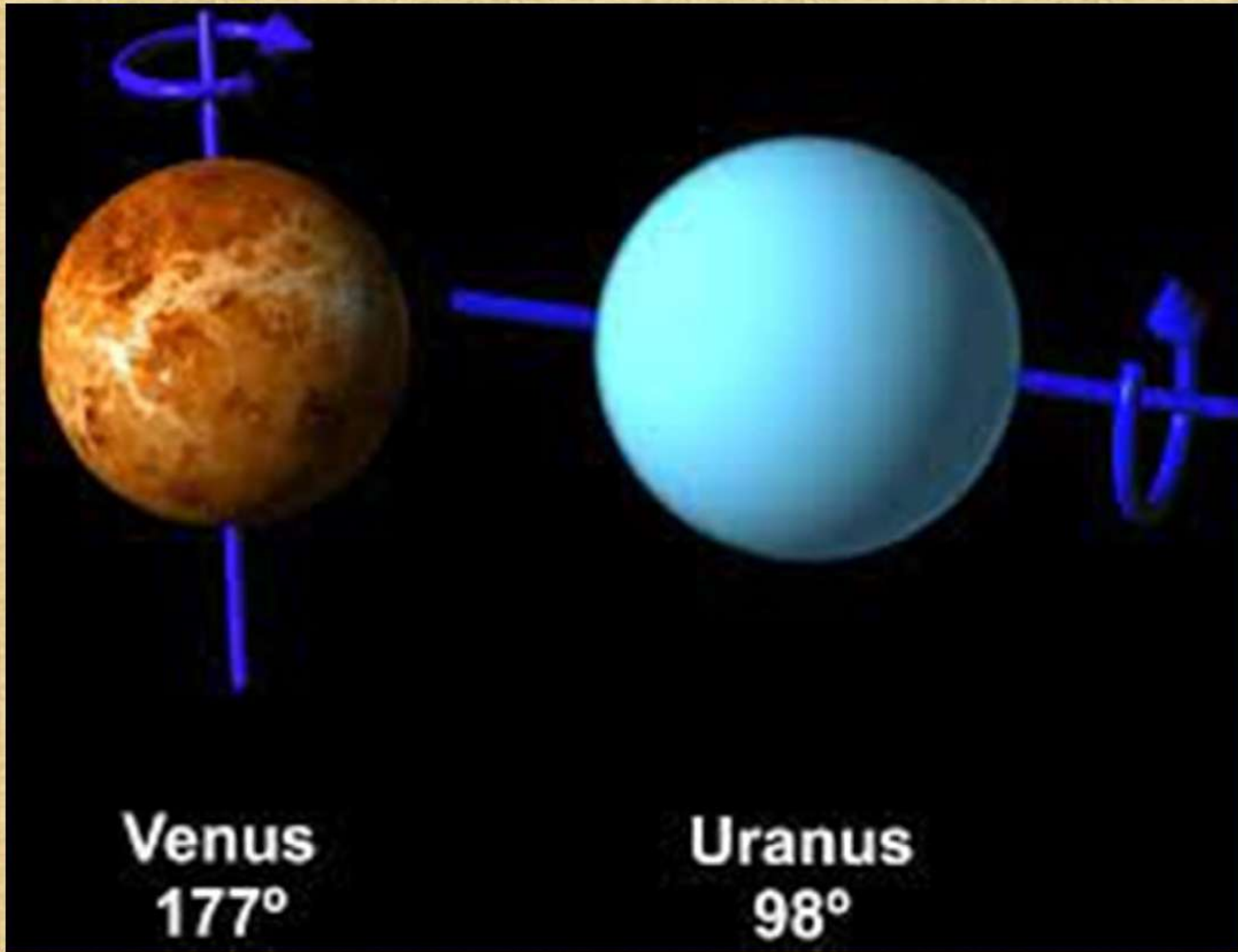
Pluto (17.2^{o})

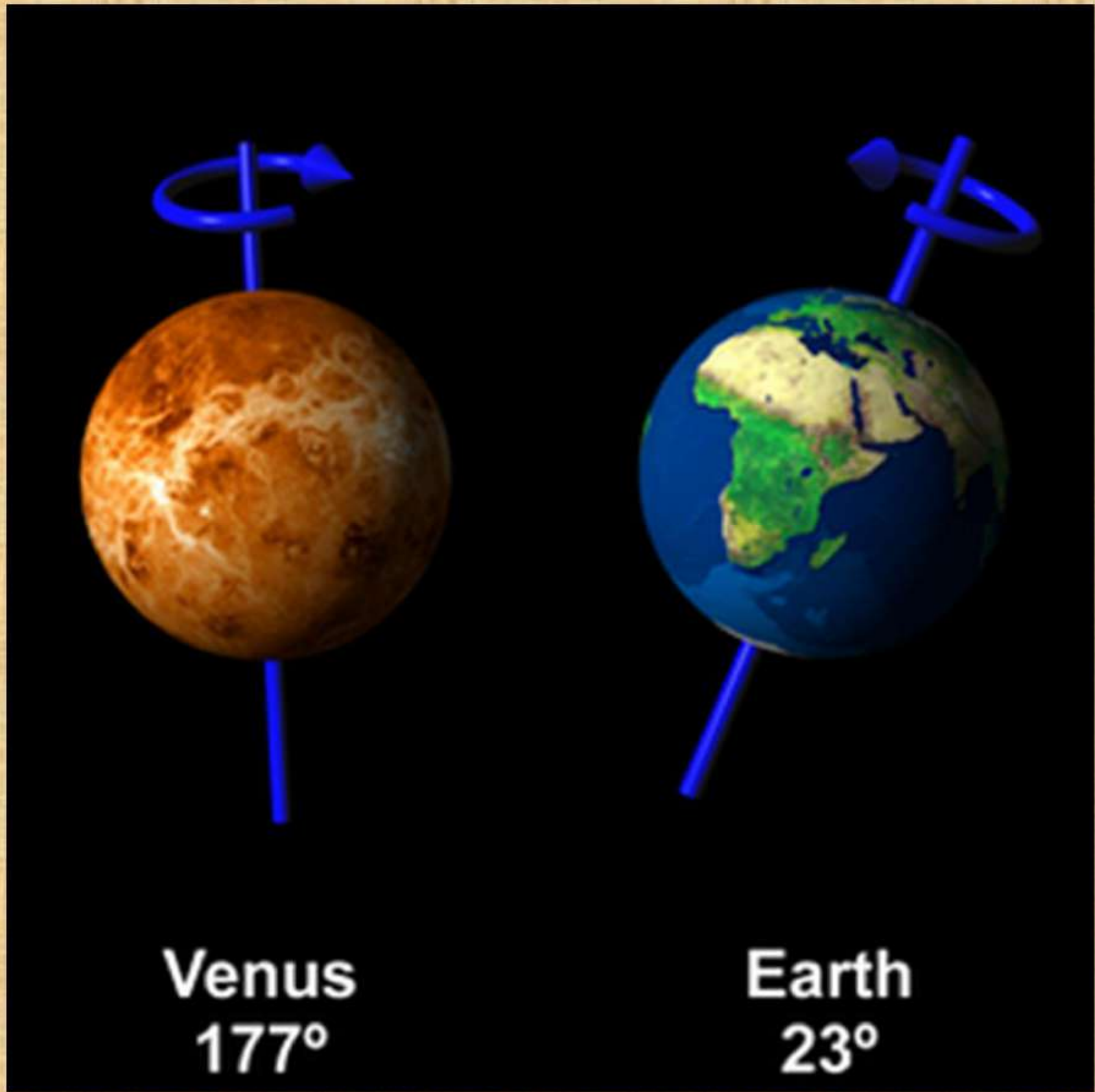
Sense of revolution: counter-clockwise

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

(Distances and times reproduced to

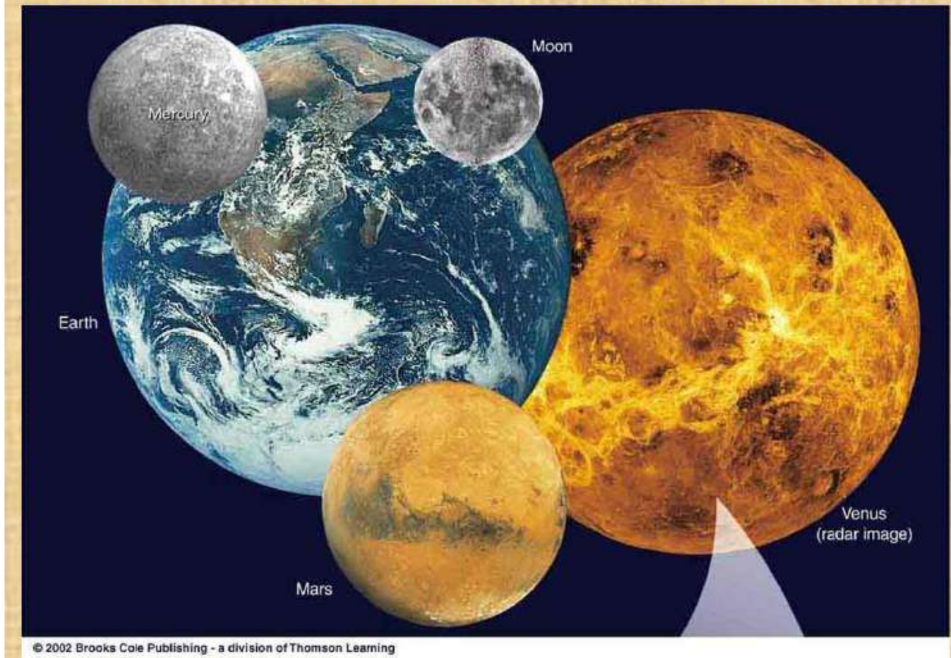

The Planets in Our Solar Sytem (not to scale)
Orbital period
88 days
Mercury
2°
176 days
Rotational period
224 days
Venus
177°
242 days
365 days
Earth
23.5°
24 hours
687 days
Mars
25°
24 h 39 m
11.86 yrs
Jupiter
3°
10 hours
29.5 yrs
Saturn
26°
10 h 39 m
84 yrs
Uranus
97°
17 h 14 m
165 yrs
Neptune
29.6°
16 hours
Dashed line shows degree of tilt in relation to Sun.
Arrow shows direction of planet's rotation.


Venus
177°
Uranus
98°

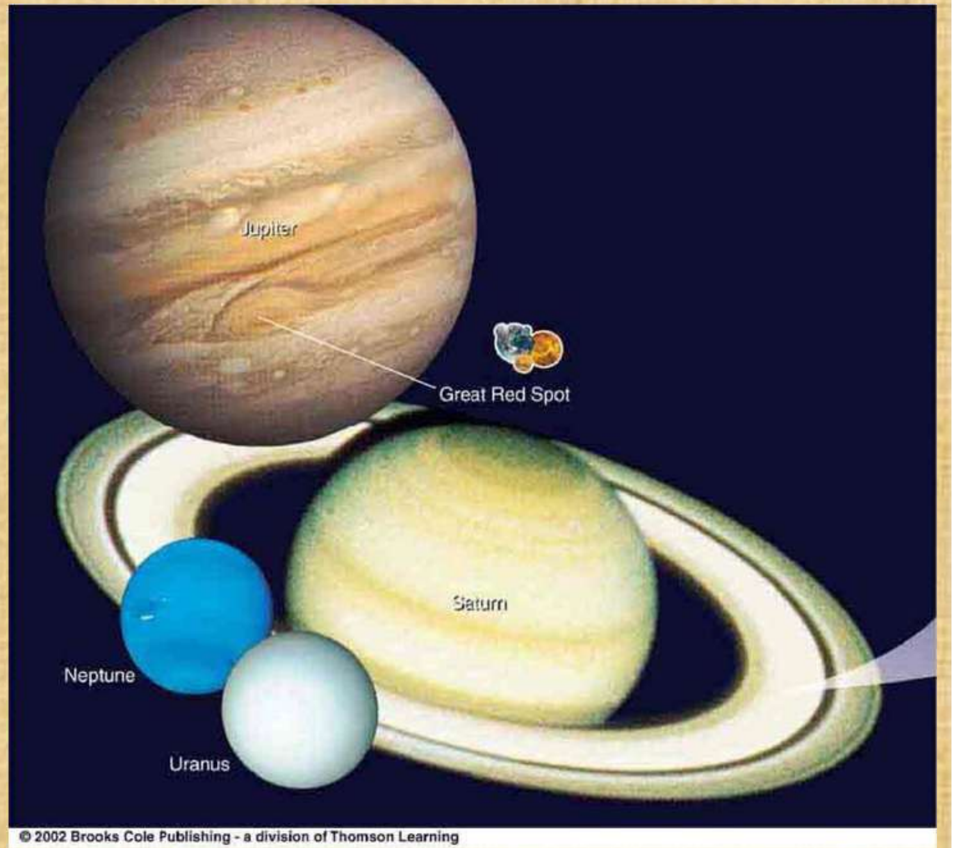

Venus
177°
Earth
23°

Two Kinds of Planets

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



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



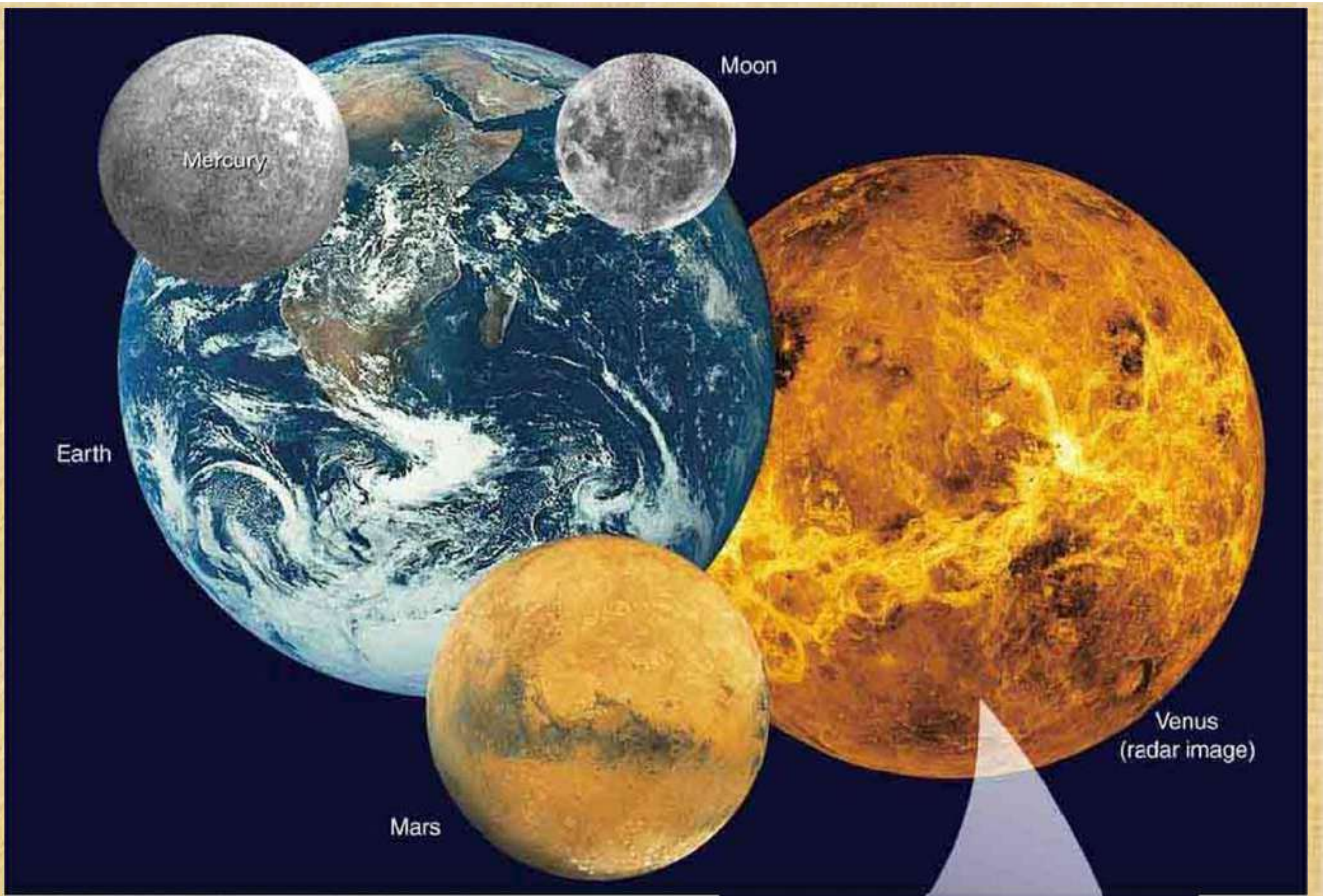
Jovian (Jupiter-like) planets: Jupiter, Saturn, Uranus, Neptune

Terrestrial Planets

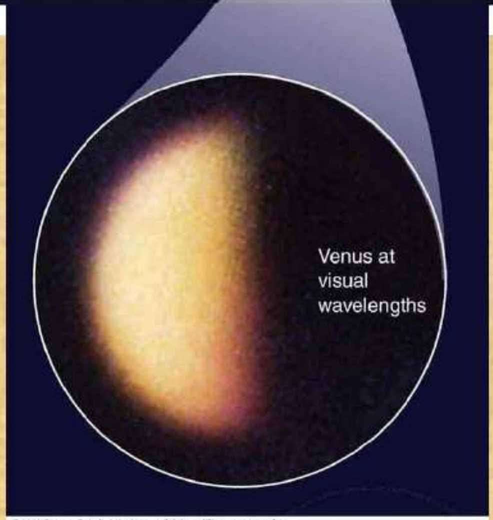
Four inner planets of the solar system

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

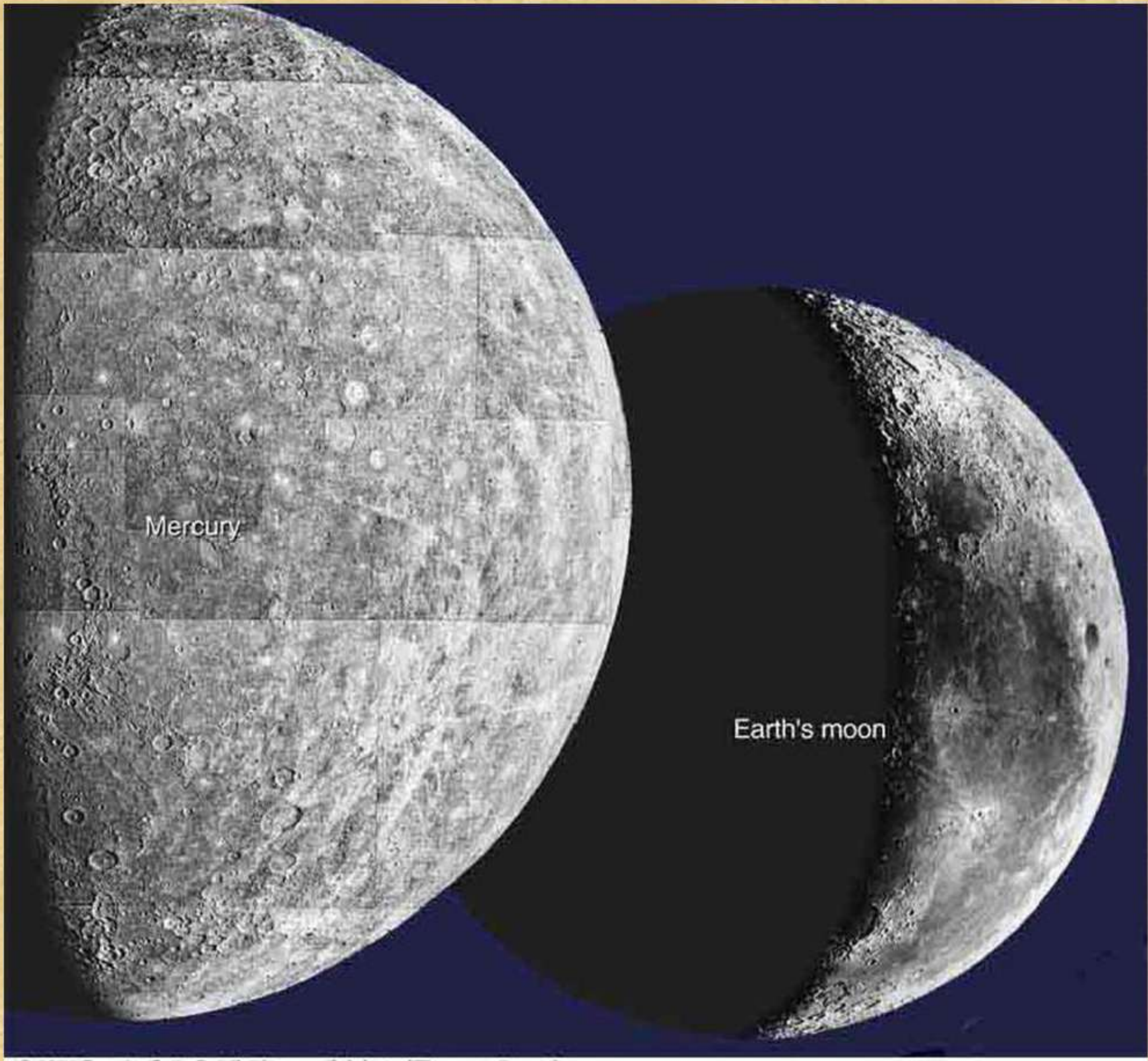
Rocky surface



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



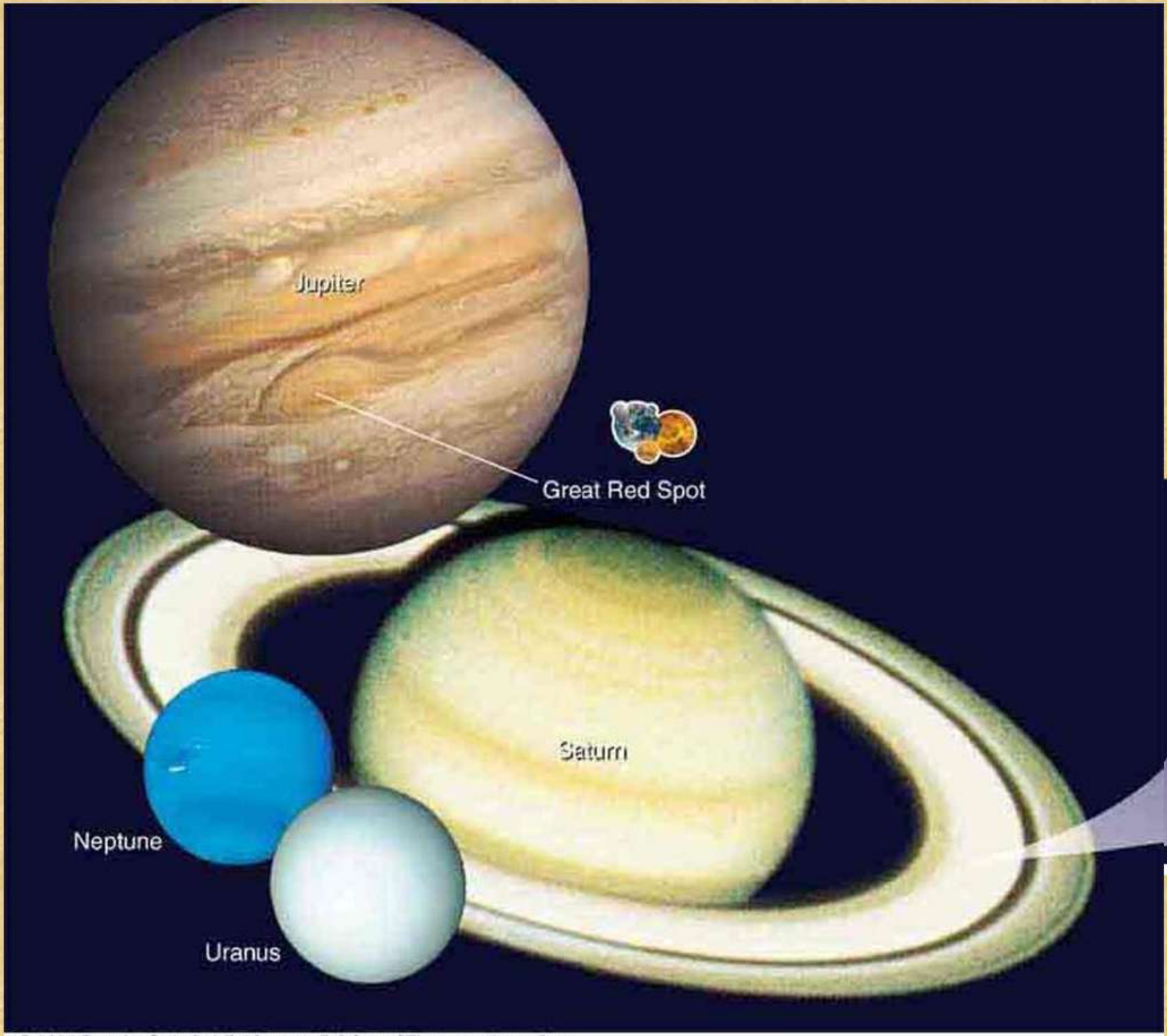
Craters on Planetsô Surfaces



Craters (like on our moonôs surface) are common throughout the solar system.

Not seen on Jovian planets because they donôt have a solid surface.

The Jovian Planets



Much larger in mass and size than terrestrial planets

Much lower average density

All have rings (not only Saturn!)

Mostly gas; no solid surface

What are the planets made of?

Element	gas or solid at Earth	Jupiter
Hydrogen	gas	gas
Helium	gas	gas
Carbon	gas	soot (solid)
Nitrogen	gas	ice
Oxygen	H_2O gas	H_2O ice
Silicon	rock	rock
Iron	metal	metal

Planet formation: Terrerstrial vs. giant planets

Giant (ñjovianò)

1. Lots of solids in the disk (cold > 5 AU)
2. Cores form from ice, rock and metal
3. Grow large, quickly (~1 million years)
4. Big enough to trap H and He gas from disk

Terrestrial (ñearth likeò)

1. Very little solid material in disk at 1 AU
2. Form from rock and metal only
3. Grow slowly (~100 million years)
4. Too small to trap any gas from disk

The Story of Planet Building

Planets formed from the same protostellar material as the sun, still found in the sunôs 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)

The Condensation of Solids

To compare densities of planets, compensate for compression due to the planetôs gravity:

Only condensed materials could stick together to form planets

Temperature in the protostellar cloud decreased outward.

Further out → Protostellar cloud cooler → metals with lower melting point condensed → change of chemical composition throughout solar system

Table 16-2 | Observed and Uncompressed Densities

Planet	Observed Density (g/cm^3)	Uncompressed Density (g/cm^3)
Mercury	5.44	5.30
Venus	5.24	3.96
Earth	5.50	4.07
Mars	3.94	3.73
(Moon)	3.36	3.35

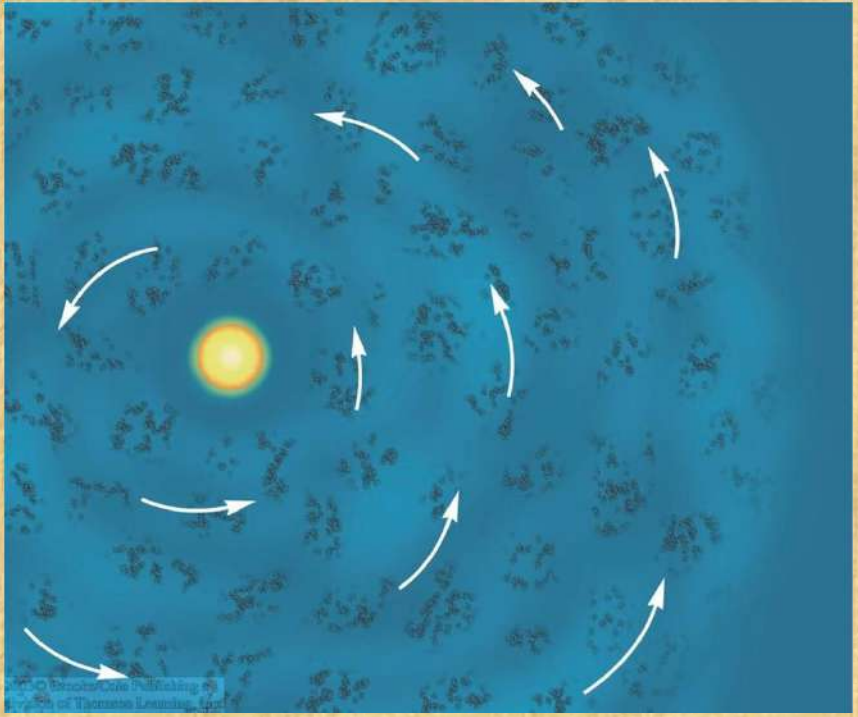
Table 16-3 | The Condensation Sequence

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)

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.

How long does life exist on Earth