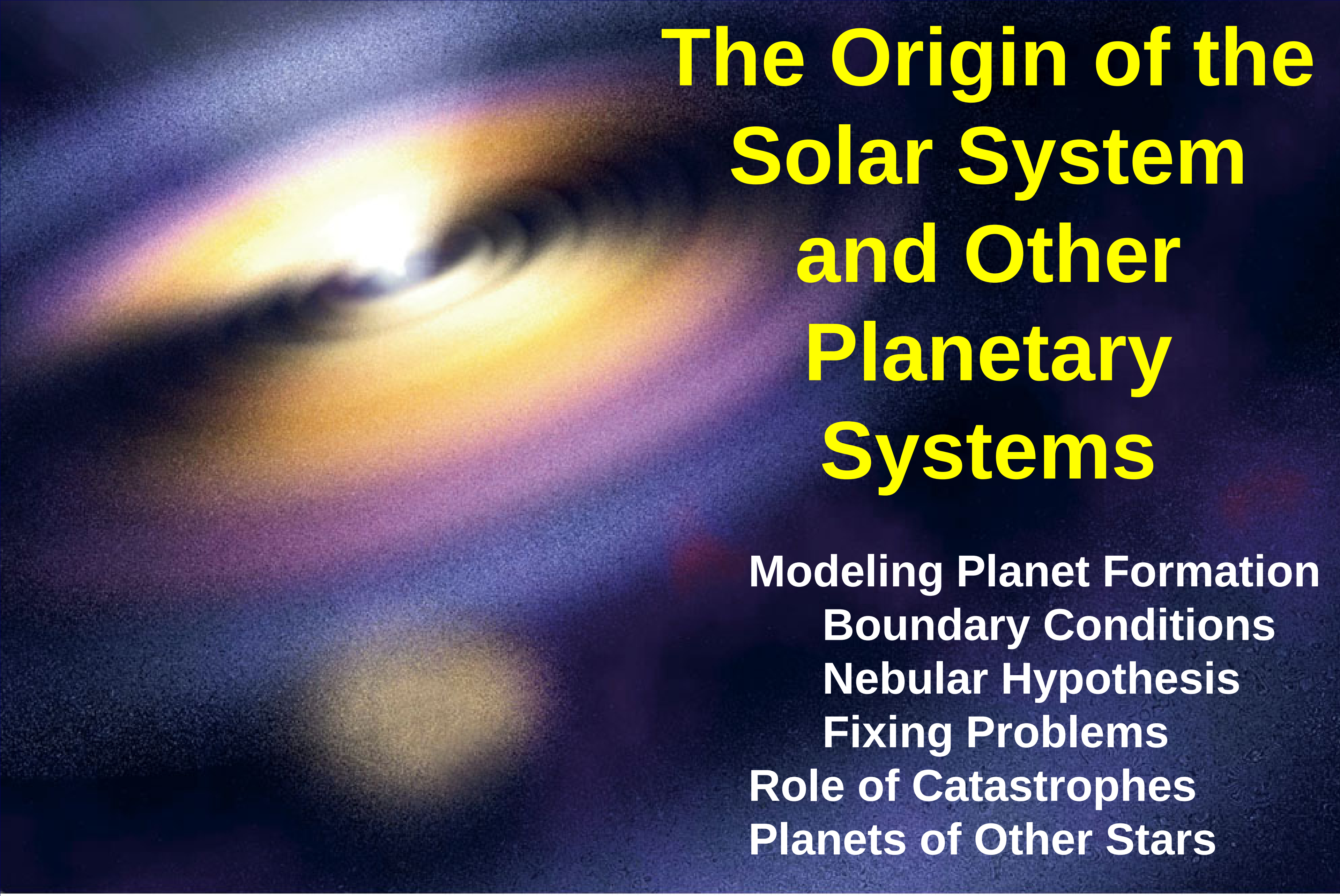
The Origin of the Solar System and Other Planetary Systems



- Modeling Planet Formation
  - Boundary Conditions
  - Nebular Hypothesis
  - Fixing Problems
- Role of Catastrophes
- Planets of Other Stars

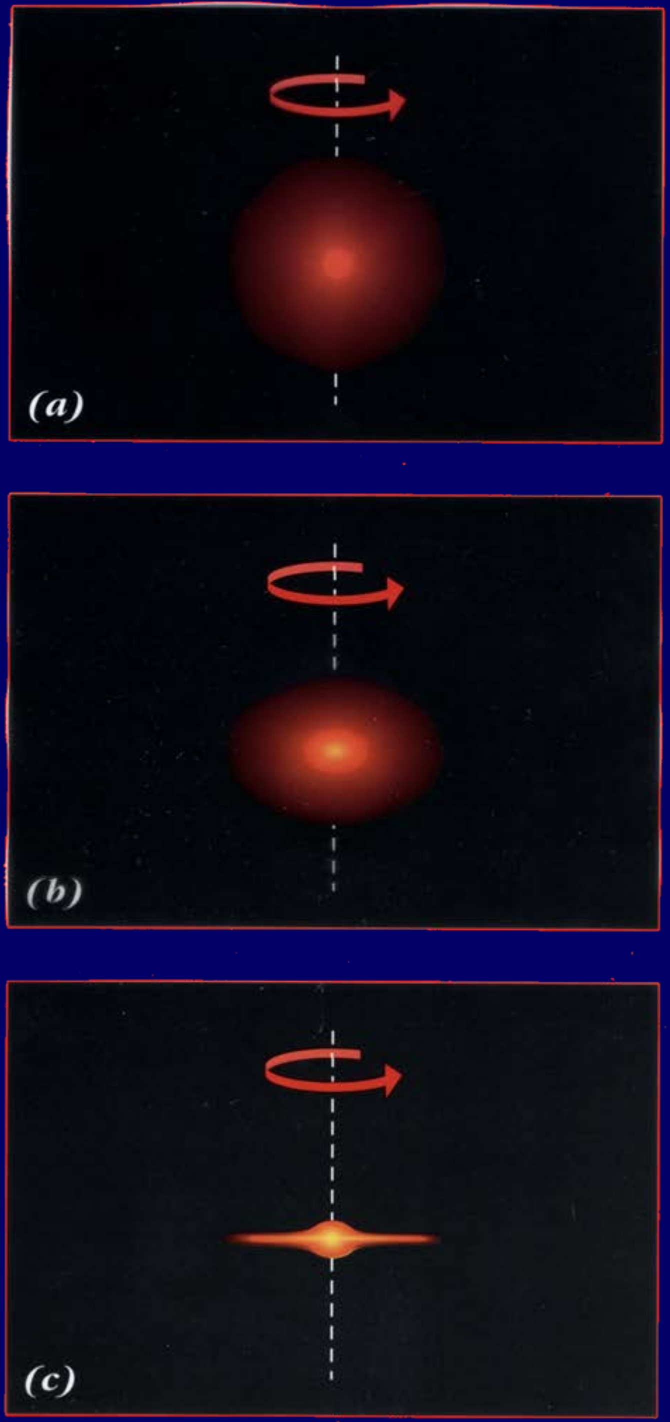
Modeling Planet Formation

Any model must explain:

1. Planets are relatively isolated in space
2. Planetary orbits are nearly circular
3. Planetary orbits all lie in (nearly) the same plane
4. Direction of orbital motion is the same as direction of Sun’s rotation (prograde revolution)
5. Direction of the rotation most planets is the same as the Sun’s rotation (prograde rotation)
6. Most satellite orbits are also in the same sense (prograde revolution)
7. Solar system is highly differentiated
8. Asteroids are very old, and not like either inner or outer planets
9. Kuiper belt, asteroid-sized icy bodies beyond the orbit of Neptune
10. Oort cloud is similar to Kuiper belt in composition, but farther out and with random orbits

Nebular Hypothesis

1. The solar system began as a rotating cloud of gas and dust.
2. It began to collapse.
3. Conservation of linear and angular momentum caused the collapsing cloud to flatten into a disk.
4. This process increased the density of the medium.
5. The center remained semi spherical because of a concentration of heat.
6. As temperatures decreased, gases could condense into liquids and solids.
7. Planetesimals formed from the accretion of condensed material and collided to form planets.



The Condensation of Solids

- To compare densities of planets, one must compensate for compression from the planet’s gravity
- Only condensed materials could stick together to form planets
- The temperature in the protostellar cloud decreased outward.
- A cooler protostellar cloud ⇒ matter with lower vaporization points condense ⇒ change of chemical composition progressing outward in the solar system

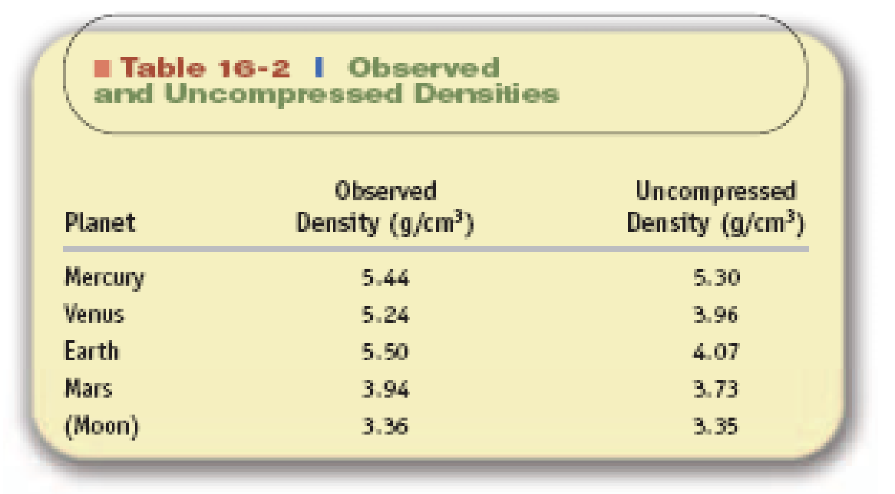


Table 16-2 | Observed and Uncompressed Densities

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

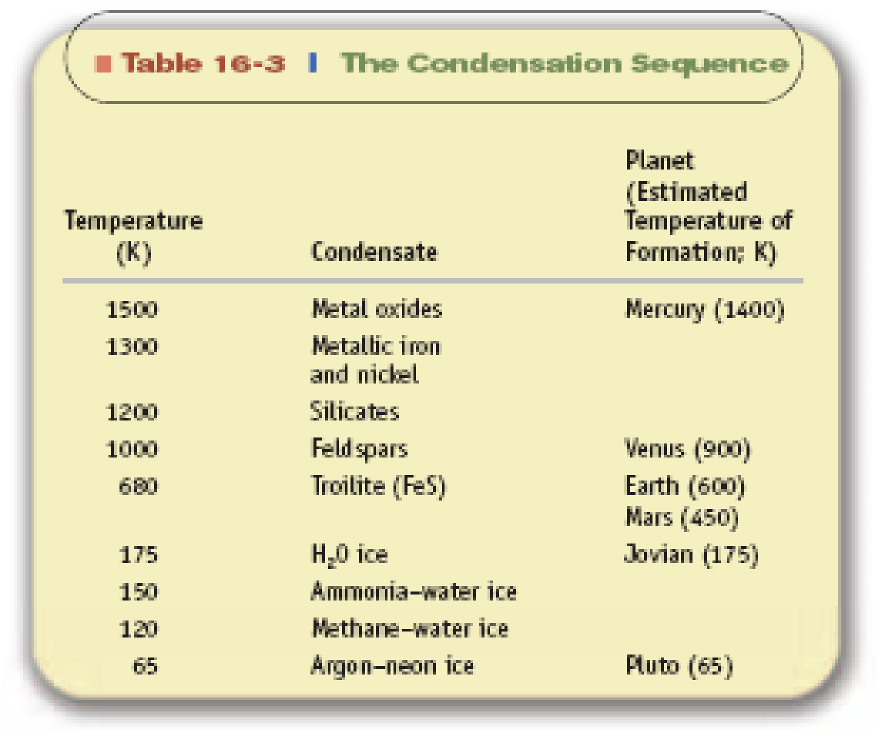
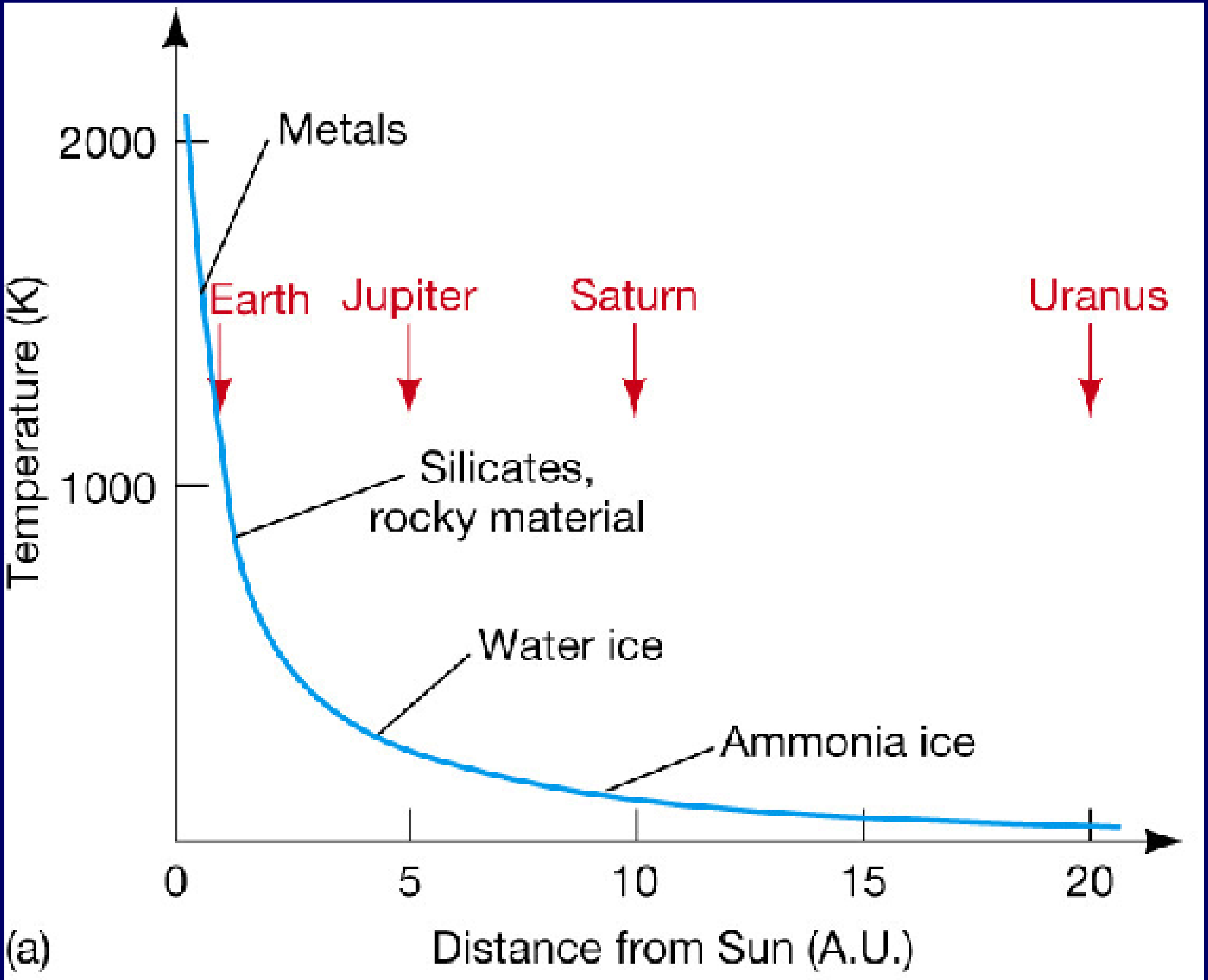


Table 16-3 | The Condensation Sequence

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)

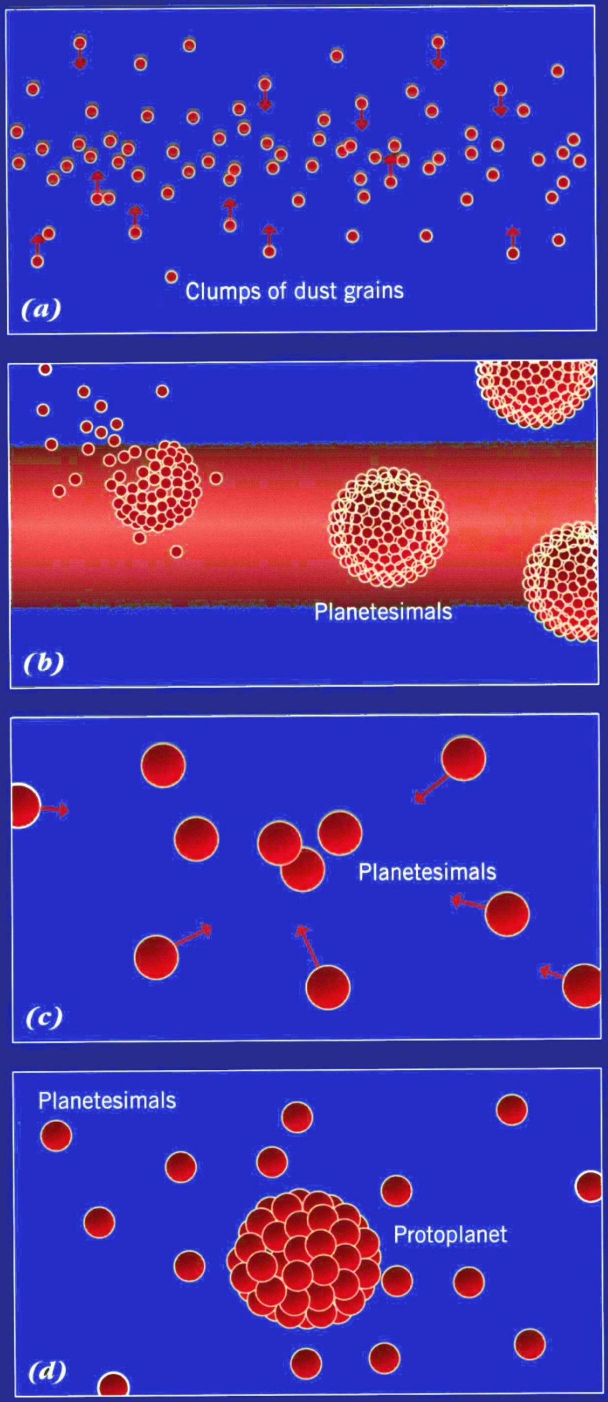
Temperature in the Solar Nebula

The temperature in the nebula determines where various materials condensed into small grains of solids or drops of liquids



Formation and Growth of Planetesimals

- After condensation, planet formation continues with the sticking together of colliding drops and grains (accretion) to form planetesimals
- Planetesimals grow from both condensation and accretion.
- Planetesimals (few cm to km in size) collide to form planets.
- Gravitational instabilities may have helped in the growth of planetesimals into protoplanets.

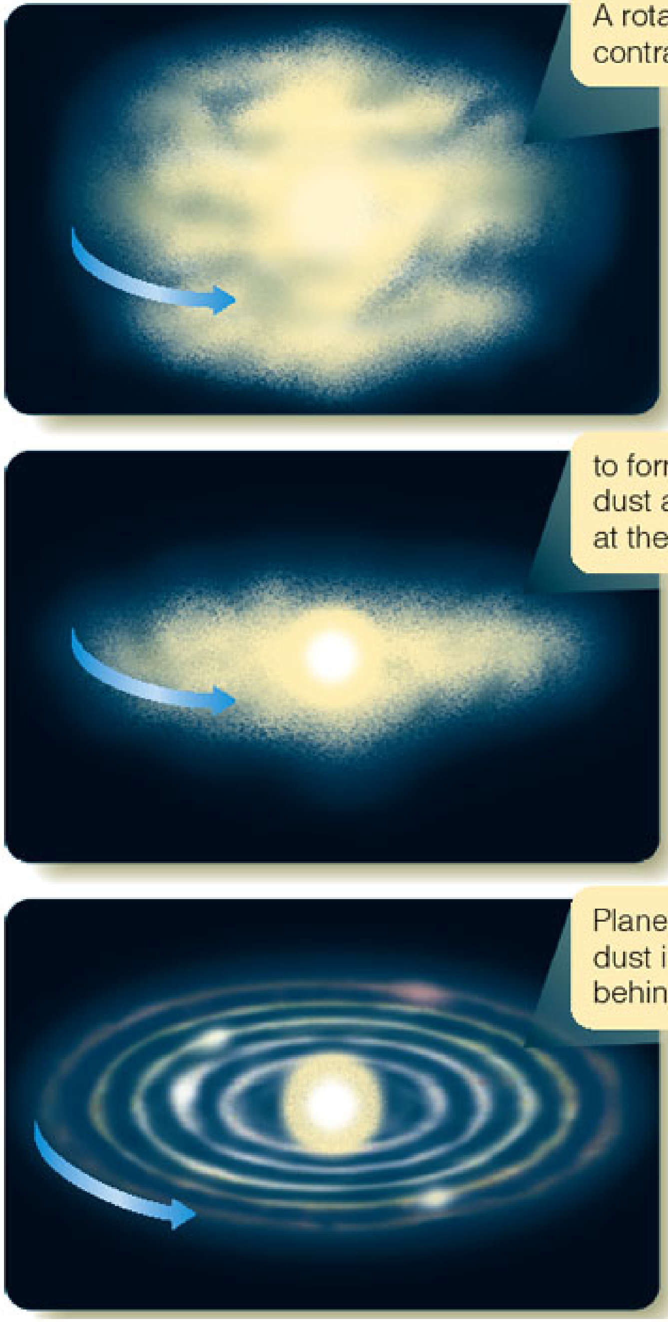


Terrestrial Planets

Accretion theory:

- A large interstellar cloud or nebula of gas and dust starts to contract, heating up from the loss of gravitational potential energy
- The Sun forms in center; dust provides condensation nuclei, around which planetesimals form
- As planets grow, they sweep up planetesimals near them, called accretion

The Solar Nebula Hypothesis



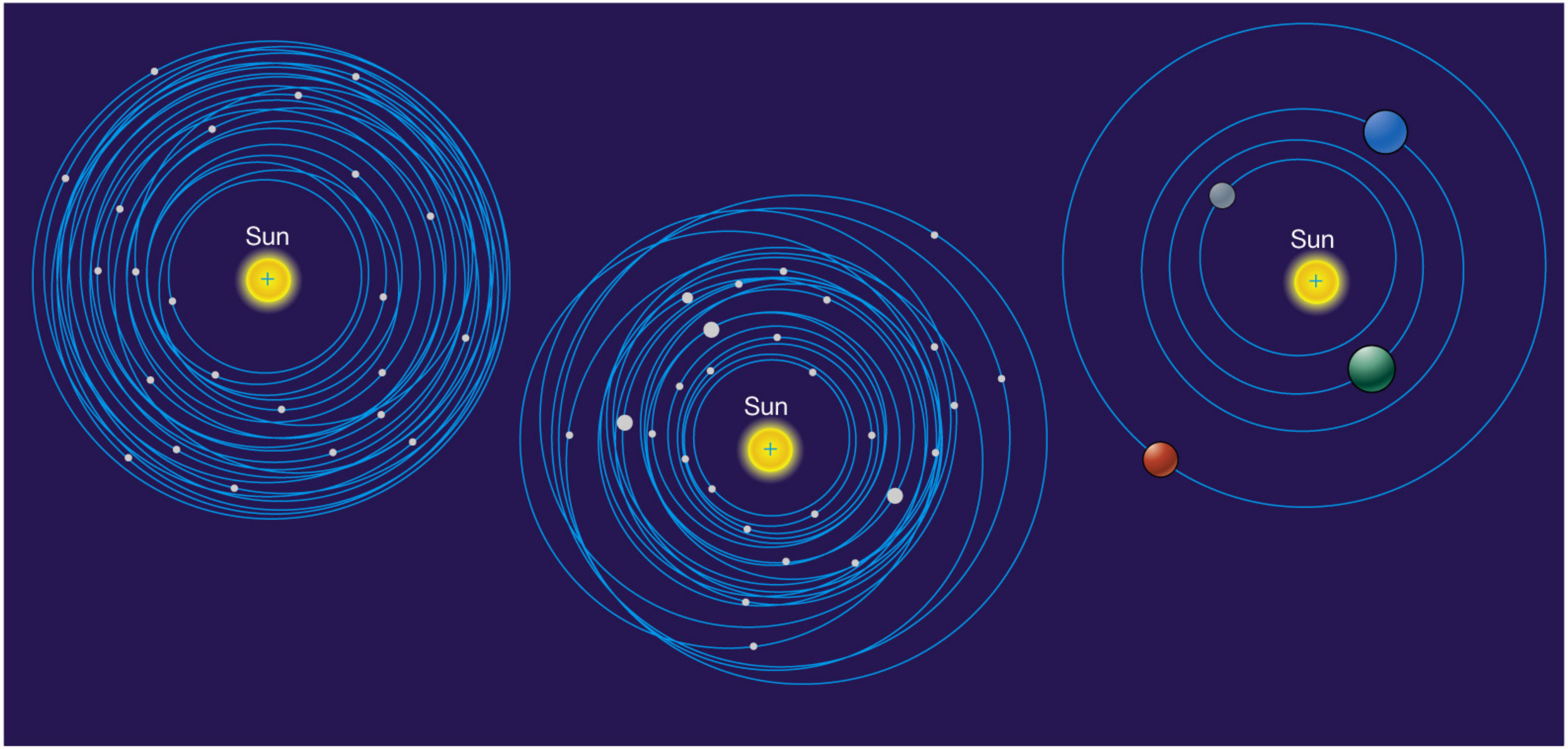
A rotating cloud of gas contracts and flattens...

to form a thin disk of gas and dust around the forming sun at the center.

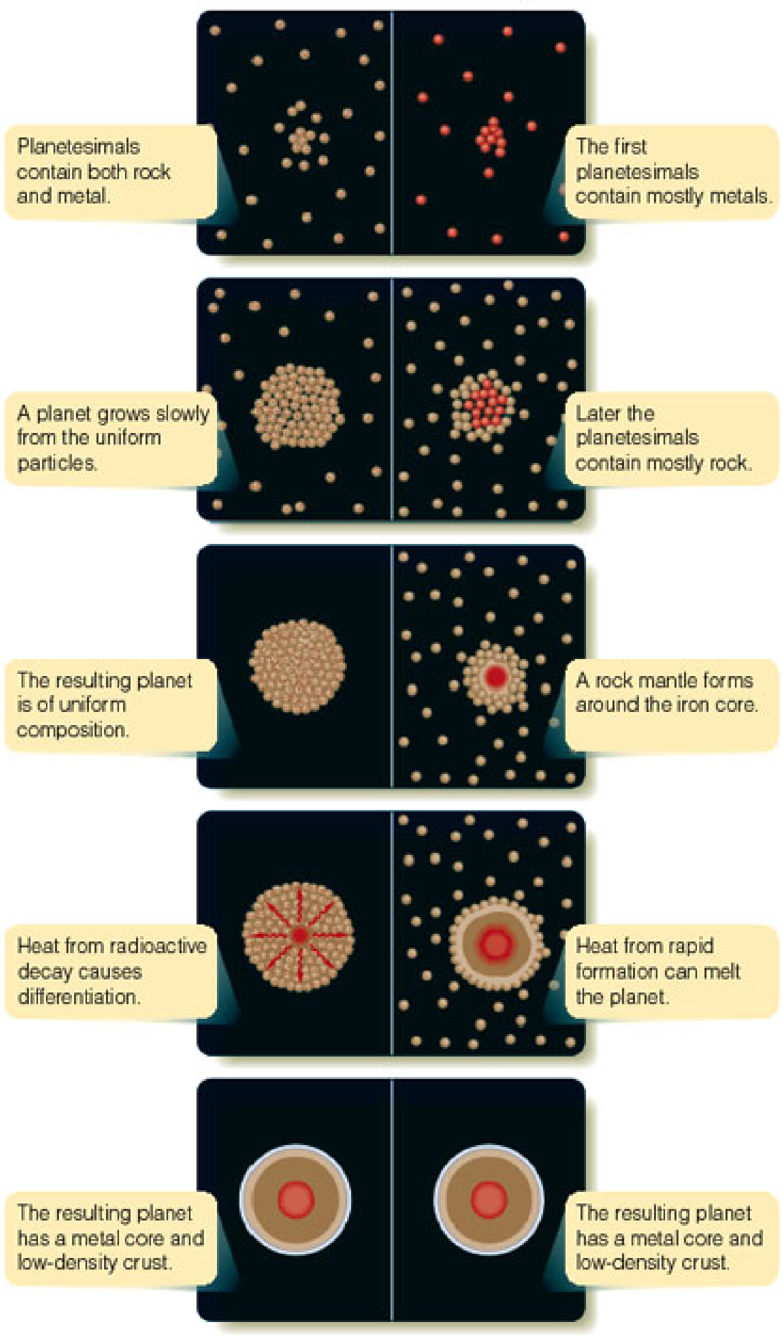
Planets grow from gas and dust in the disk and are left behind when the disk clears.

Differentiation in the Solar System

Terrestrial (rocky) planets formed near the Sun, where temperatures were higher – ices could not condense there



The Growth of Protoplanets


Two Models of Planet Building

The simplest form of planet growth:

Unchanged composition of accreted matter over time

As rocks melted, heavier elements sank to the center ⇒ differentiation

Gas is released from a hot interior (outgassing) ⇒ production of a secondary atmosphere

A variation of this scenario:

Gradual change of accreted grain composition resulting from the cooling nebula which allows volatile materials to condense after the accretion of refractory materials—differential accretion

The Giant Planet Problem

Two problems for the theory of giant planet formation:

1) Observations of extrasolar planets indicate that giant planets are common.
2) The radiation from nearby massive stars causes protoplanetary disks to evaporate quickly (typically within ~100,000 years).

$\Rightarrow$ Too short for giant planets to grow!

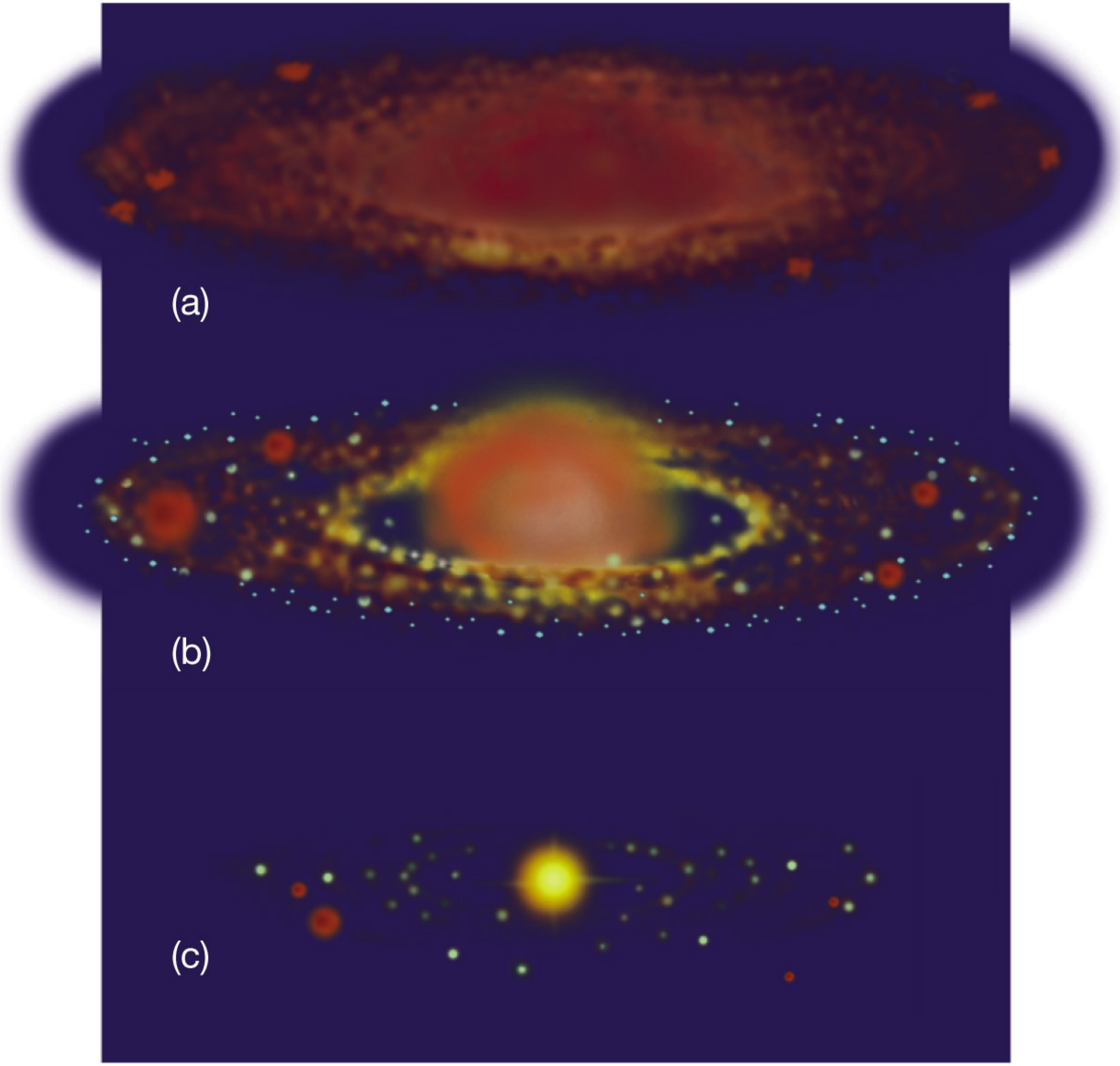
Solution:

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

Giant Planets

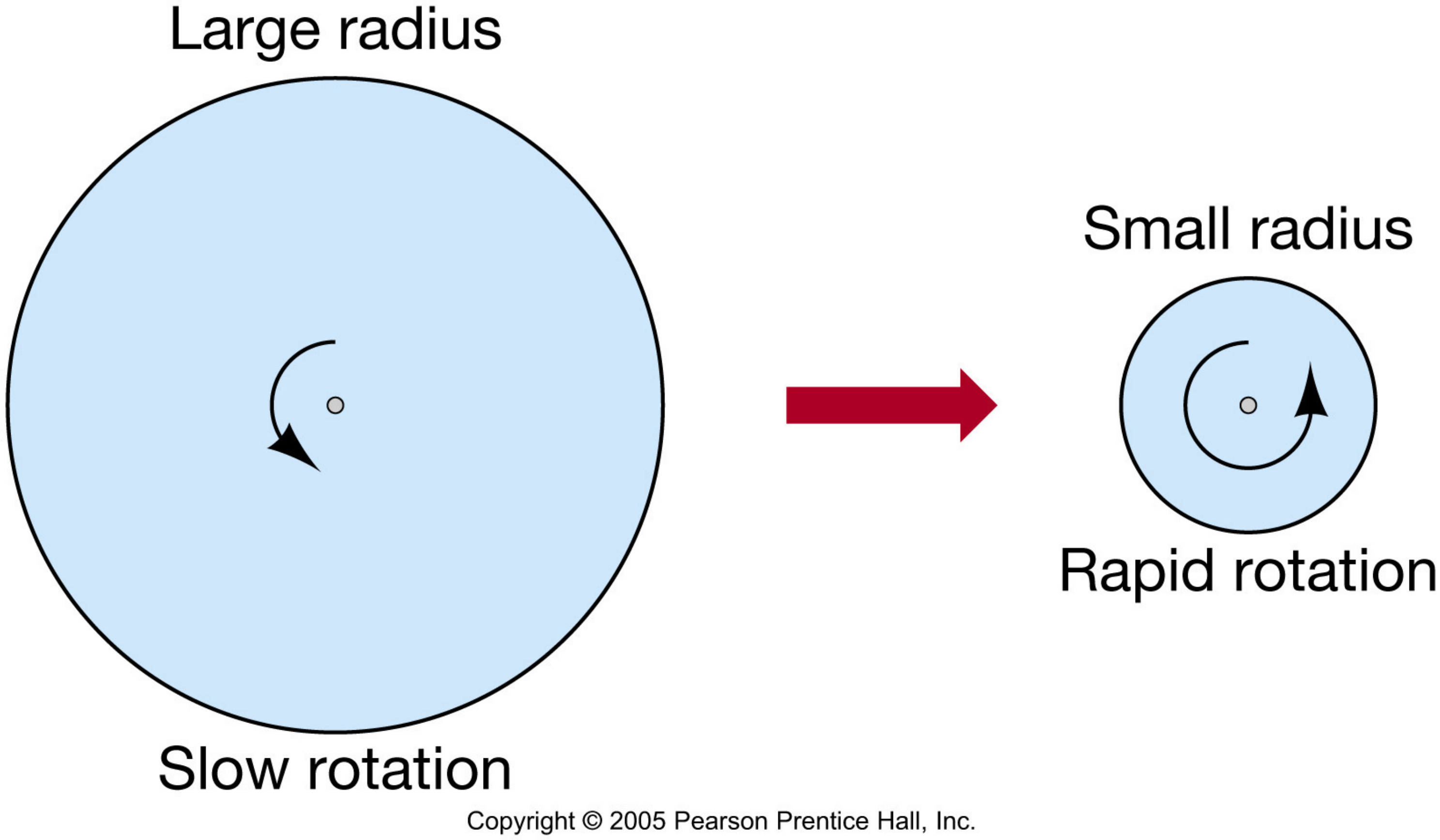
Giant planets:

- Started accreting like terrestrial planets from more abundant ices
- They grew quickly
- Once they were large enough, they probably captured gas directly from the contracting nebula
- They may have formed from instabilities in the outer, cool regions of the nebula



Solar Rotation Problem

Conservation of angular momentum requires that the product of radius and rotation rate must be constant for a particle. This implies that the Sun should be rotating much more rapidly than it does.



Two bodies of the same mass and different radii can have the same angular momentum, if the body of smaller radius has a comparably larger rotation speed

Solar Rotation Problem

As it collapsed, the solar nebula had to conserve its angular momentum

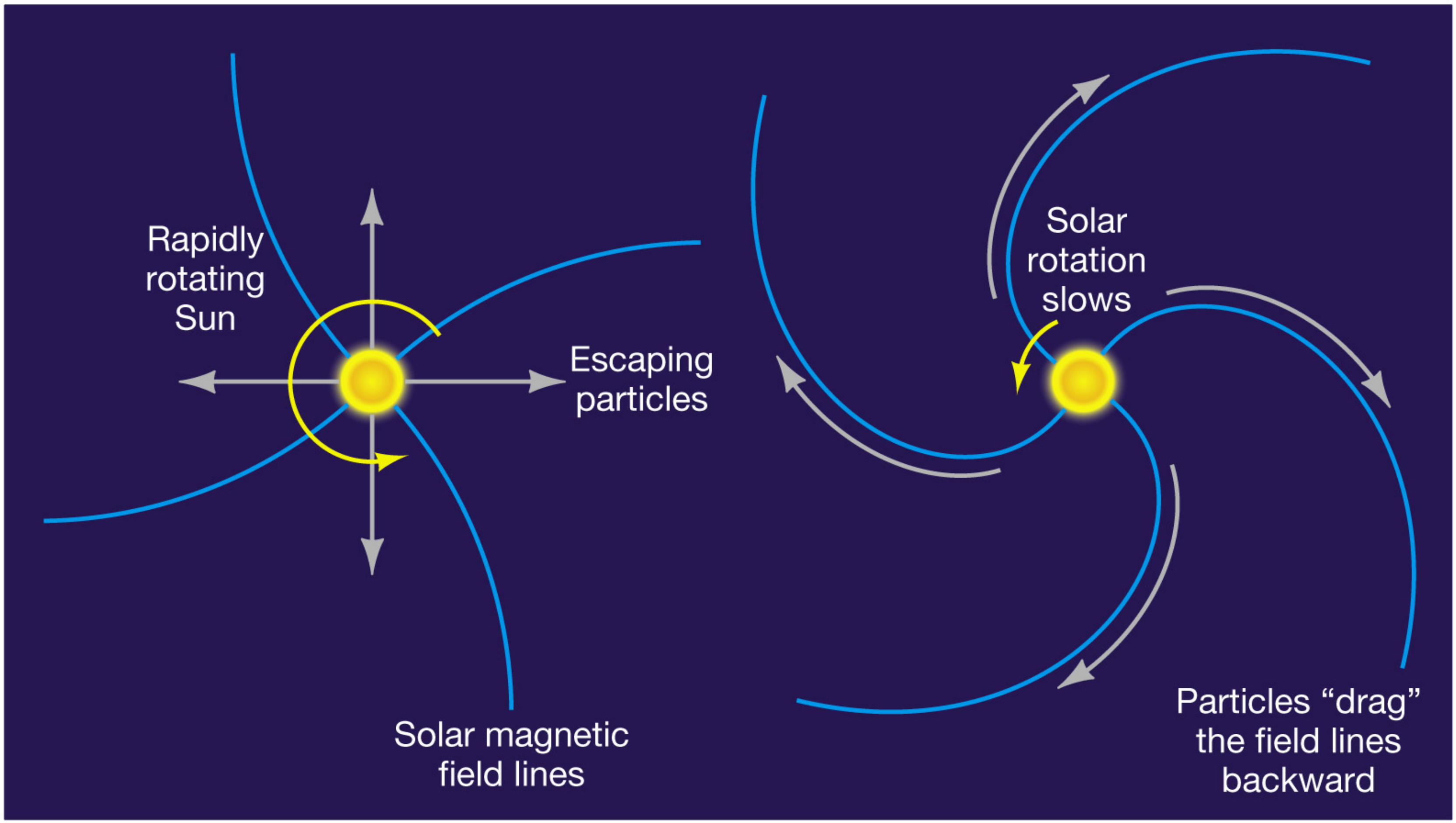
However, now, the Sun has almost none of the solar system's angular momentum

- Jupiter alone accounts for 60%
- Four giant planets account for more than 99%

Why doesn't the Sun rotate more rapidly?

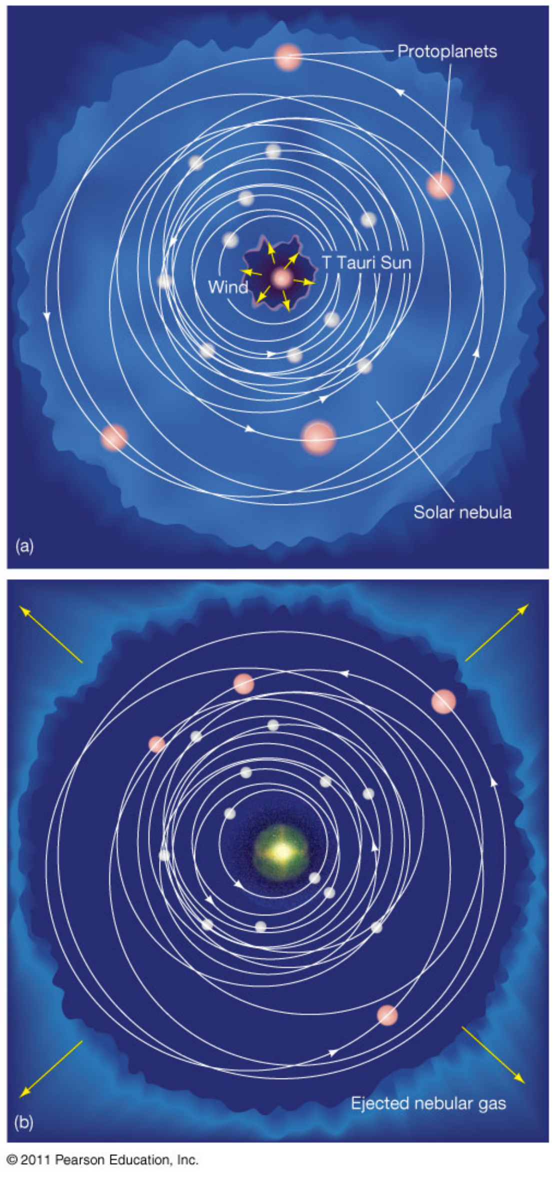
Solar Rotation Problem

Hypothesis: The Sun transferred most of its angular momentum to outer planets (and interstellar space) as a result of friction from the magnetic drag of field lines passing through a conducting plasma (magnetic braking).



Solar Rotation Problem

The plausibility of magnetic breaking from a strong solar wind can be found in T Tauri stars which are in a highly active phase of their evolution and have strong stellar winds. Besides being a source of magnetic braking, these winds also sweep away the gas disk, leaving the planetesimals and gas giants.



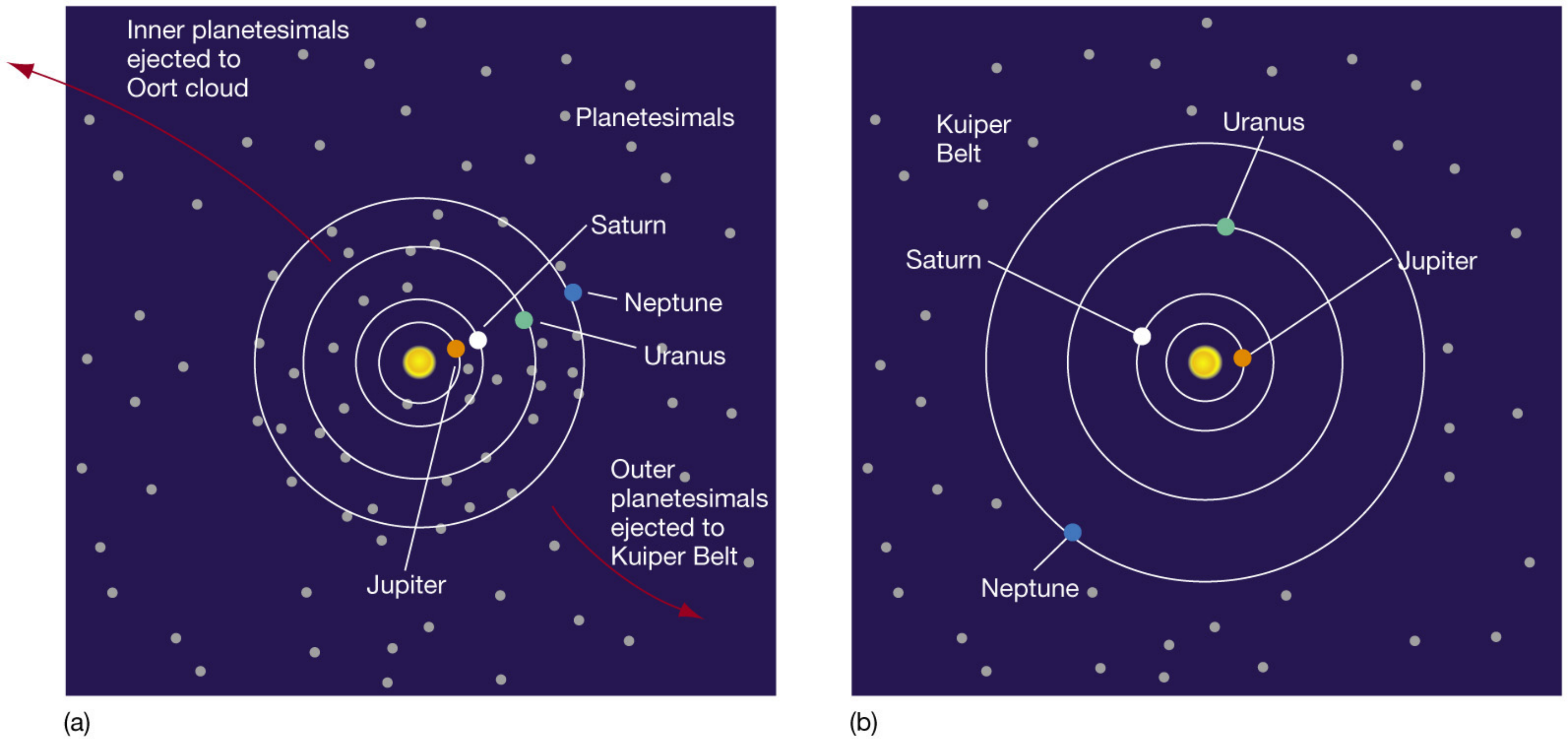
Asteroid Problem

Why is there an asteroid belt?

- Orbits mostly between Mars and Jupiter
- Jupiter’s gravity inhibited planetesimals from condensing into a planet or accreting onto an existing one although a few dwarf planets were formed
- This implies that most asteroids are essentially planetesimals left over from the initial formation of the solar system
- Some asteroid families are debris of larger asteroids that were broken apart in a collision

Kuiper Belt and Oort Cloud

Icy planetesimals far from the Sun have remained as Kuiper belt bodies. Some of these were ejected into distant orbits by gravitational interaction with the giant planets forming the Oort cloud. Oort cloud objects have very eccentric orbits and occasionally appear in the inner solar system as comets.

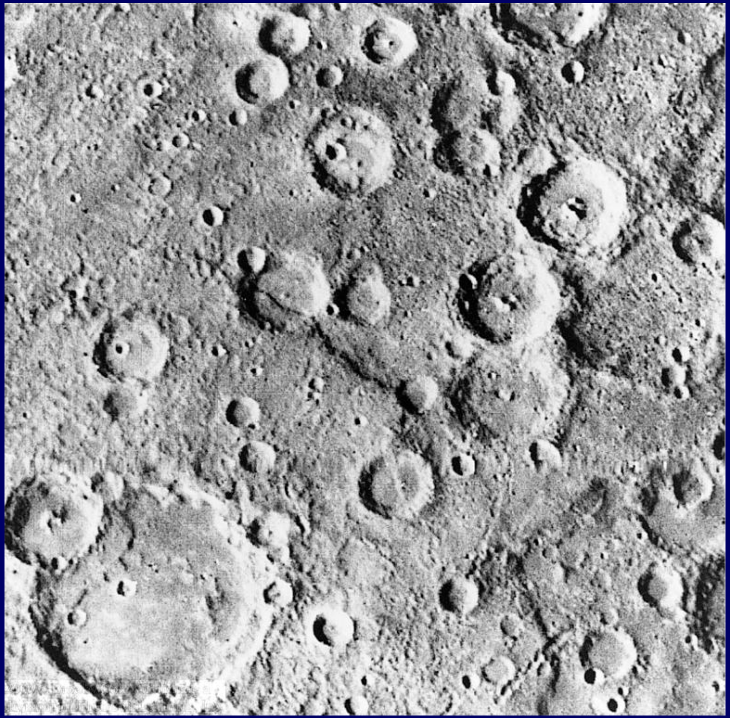


(a) (b)

Clearing the Nebula

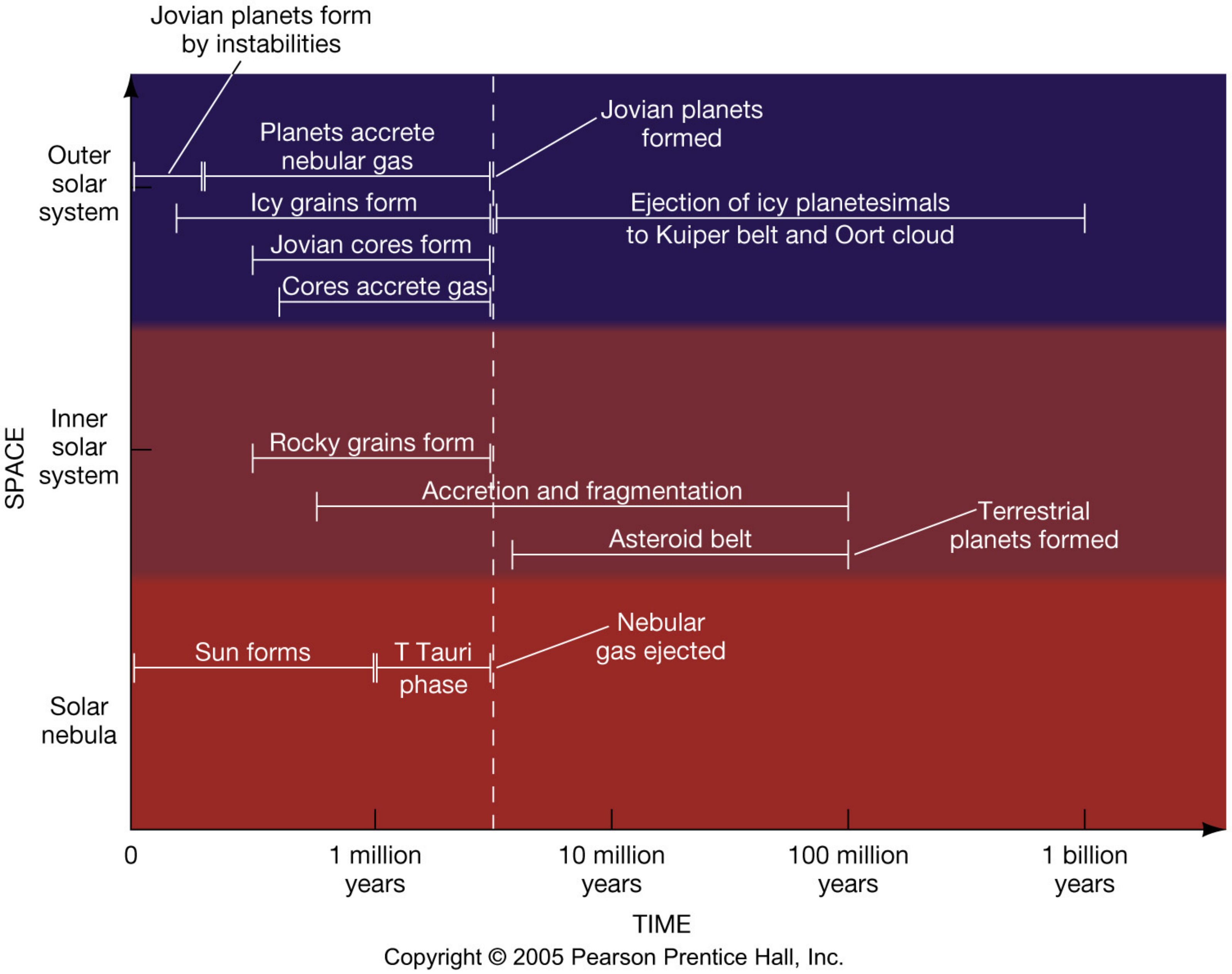
Remains of the protosolar nebula were cleared away by:

- **Radiation pressure of the Sun**
- **Solar wind**
- **Sweeping-up of space debris by planets**
- **Ejection by close encounters with planets**



Surfaces of the Moon and Mercury show evidence for heavy bombardment by asteroids sweeping-up some the debris.

Timeline of Solar System Formation



The Role of Catastrophes

Condensation-accretion theory explains the 10 properties of the solar system mentioned at the beginning.

However, there are special cases not explained by the theory.

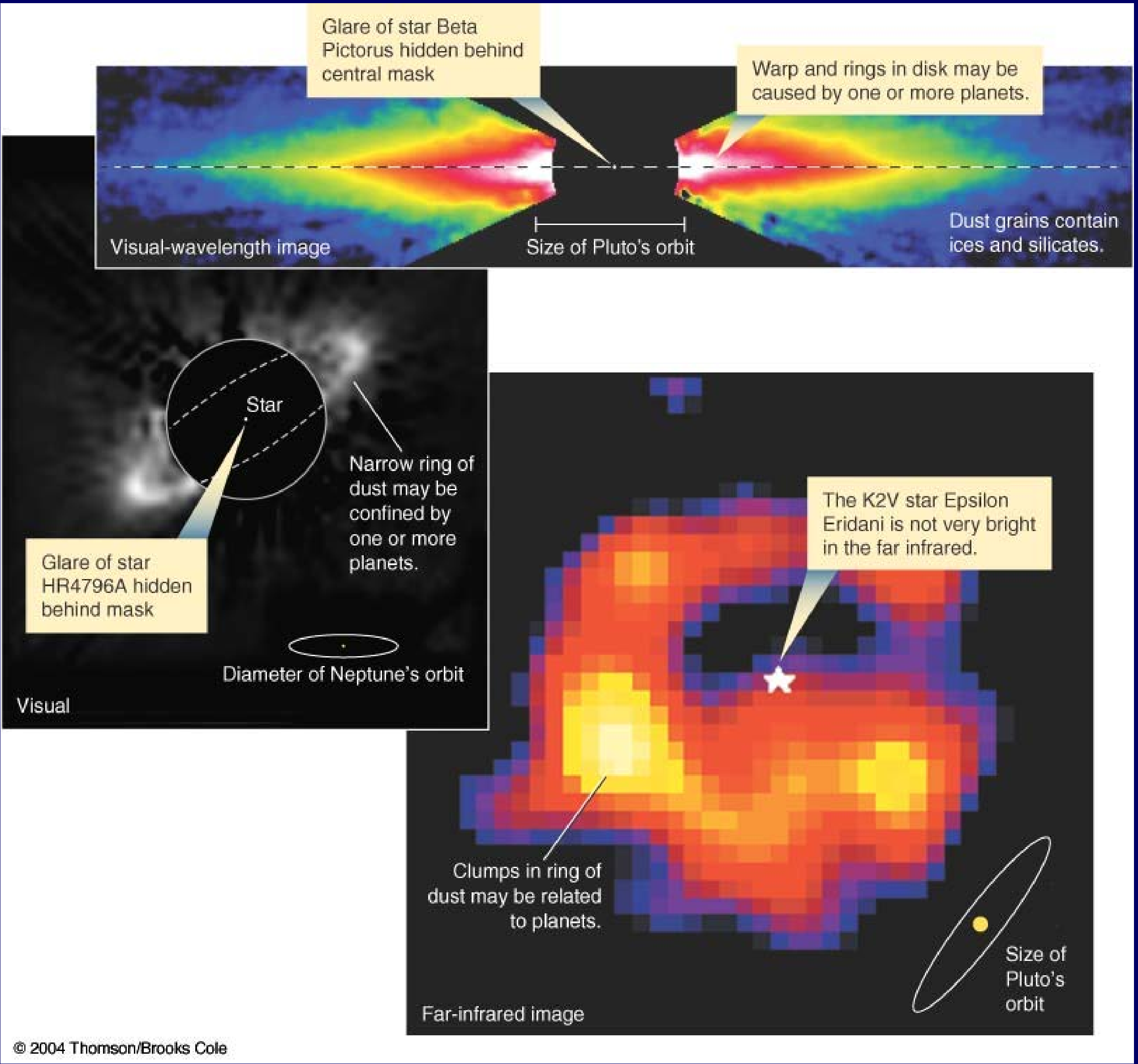
1. Mercury’s large metallic core may be the result of a collision between two planetesimals, where much of the mantle was lost.
2. Two large bodies may have merged to form Venus.
3. Earth–Moon system may have formed after a collision.
4. A late collision may have caused Mars’ north–south asymmetry and stripped most of its atmosphere.
5. Uranus’ tilted axis may be the result of a glancing collision.
6. Miranda may have been almost destroyed in a collision.
7. Interactions between giant protoplanets and planetesimals could be responsible for irregular satellites.
8. Pluto is probably a large Kuiper-belt object.

The Role of Catastrophes

- Many of these explanations have one thing in common – a catastrophic, or near-catastrophic, collision at a critical time during formation.
- Normally, one does not like to explain things by calling on one-time events, but it is clear that the early solar system involved almost constant collisions. Some must have been exceptional.
- Collisions can give predictable results when large numbers of them can be treated statistically. However, there are always statistical outliers that produce extraordinary results.

Planets of Other Stars

The theory of planet formation has planets evolving from a stellar nebula.



Since most stars form from a stellar nebula ⇒ Many stars should have planets!

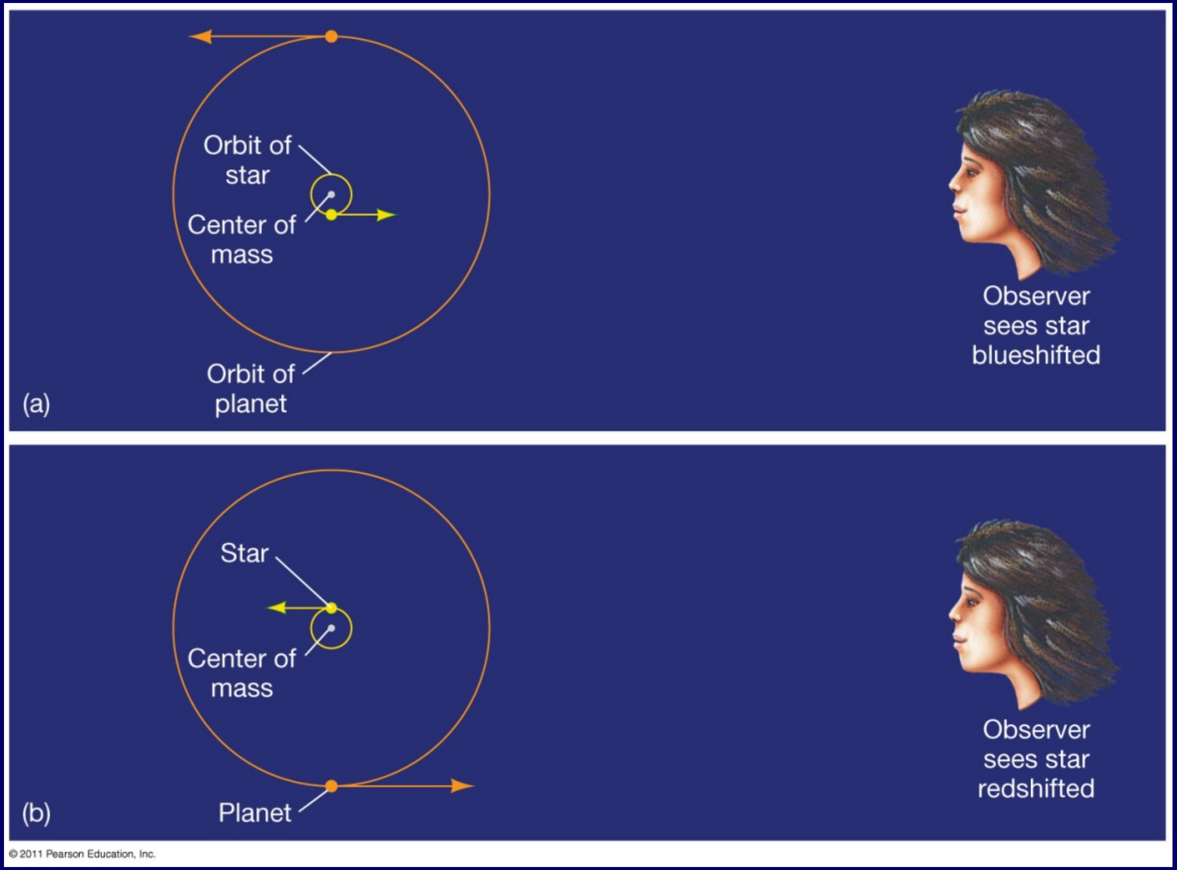
Most other planets cannot be imaged directly.

How are they found?

We look for “wobbling” motion of the star around the common center of mass with its planetary system.

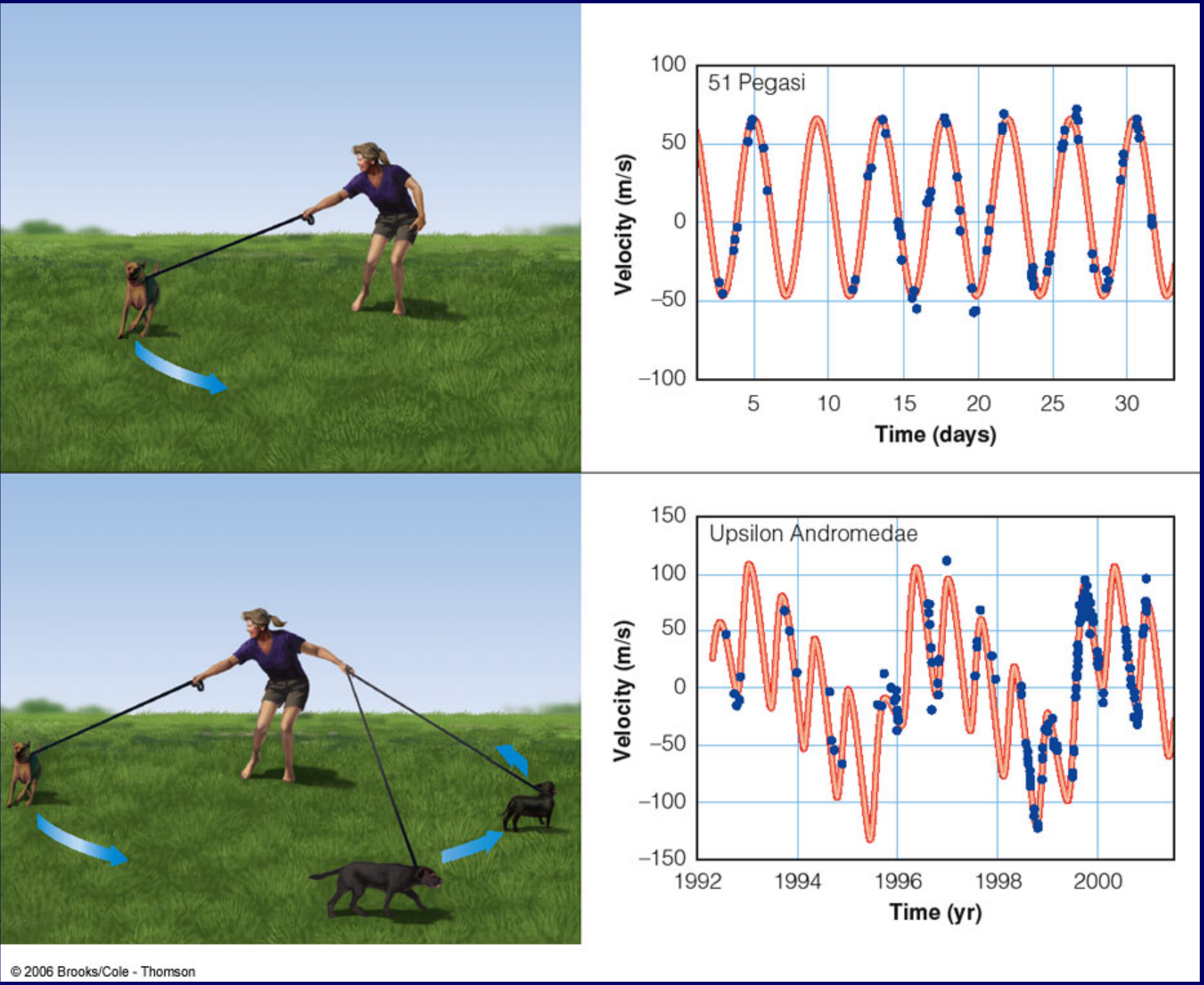
Searching for Extrasolar Planets

Planets around other stars can be detected if they are large enough to cause the star to "wobble" as the planet and star orbit around their common center of mass.



If the "wobble" is longitudinal to our line of sight, it can also be detected through the Doppler shift as the star's motion changes.

Searching for Extrasolar Planets



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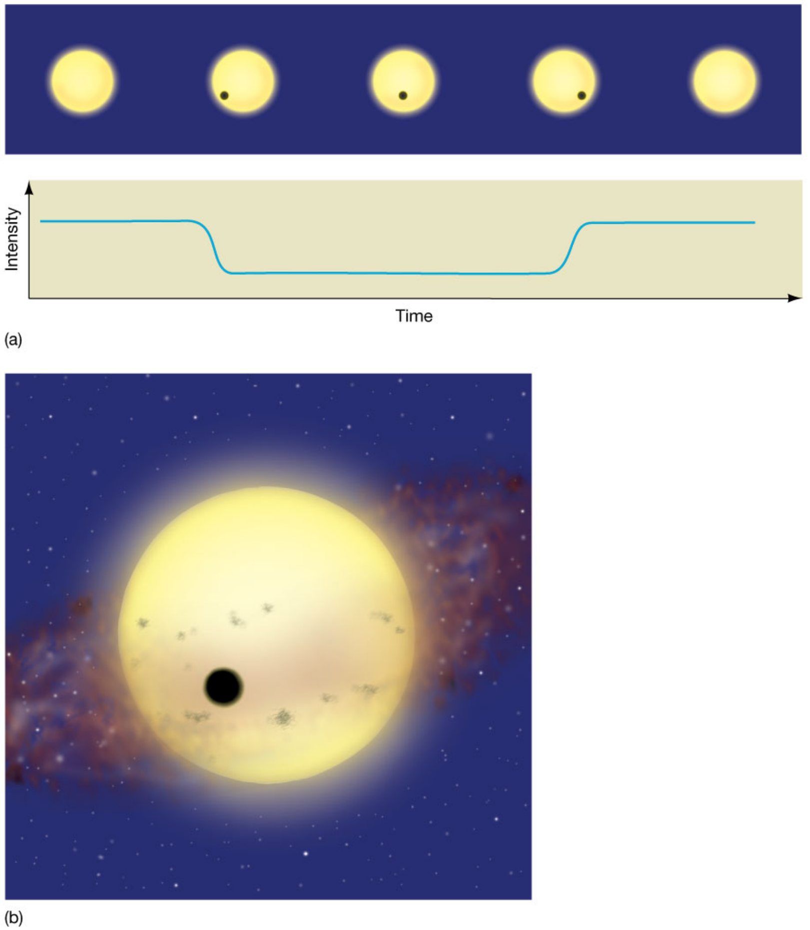
We can observe periodic Doppler shifts of stars with no visible companion which is evidence for the wobbling motion of the star around the common center of mass of a planetary system

Searching for Extrasolar Planets

An extrasolar planet may also be detected if its orbit lies in the plane of the line of sight to us. The planet will then eclipse the star, and if the planet is large enough, some decrease in luminosity may be observed.

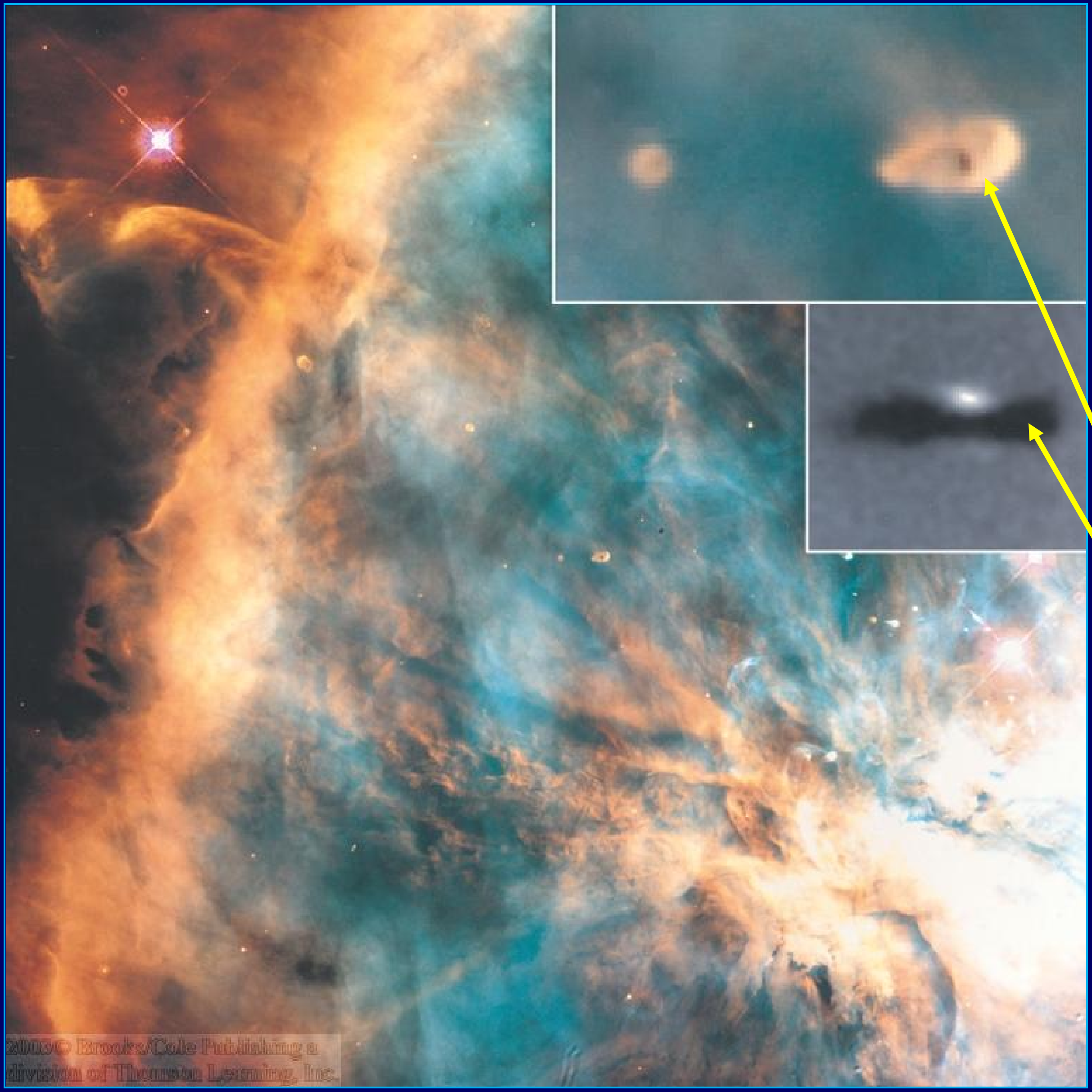


Planets of Other Stars

Over 450 extrasolar planets have been found so far and more are being found rapidly

- Most have masses comparable to Jupiter’s mass
- Orbits are much smaller, and in some cases very much smaller, than the orbit of Jupiter
- Orbits have high eccentricity

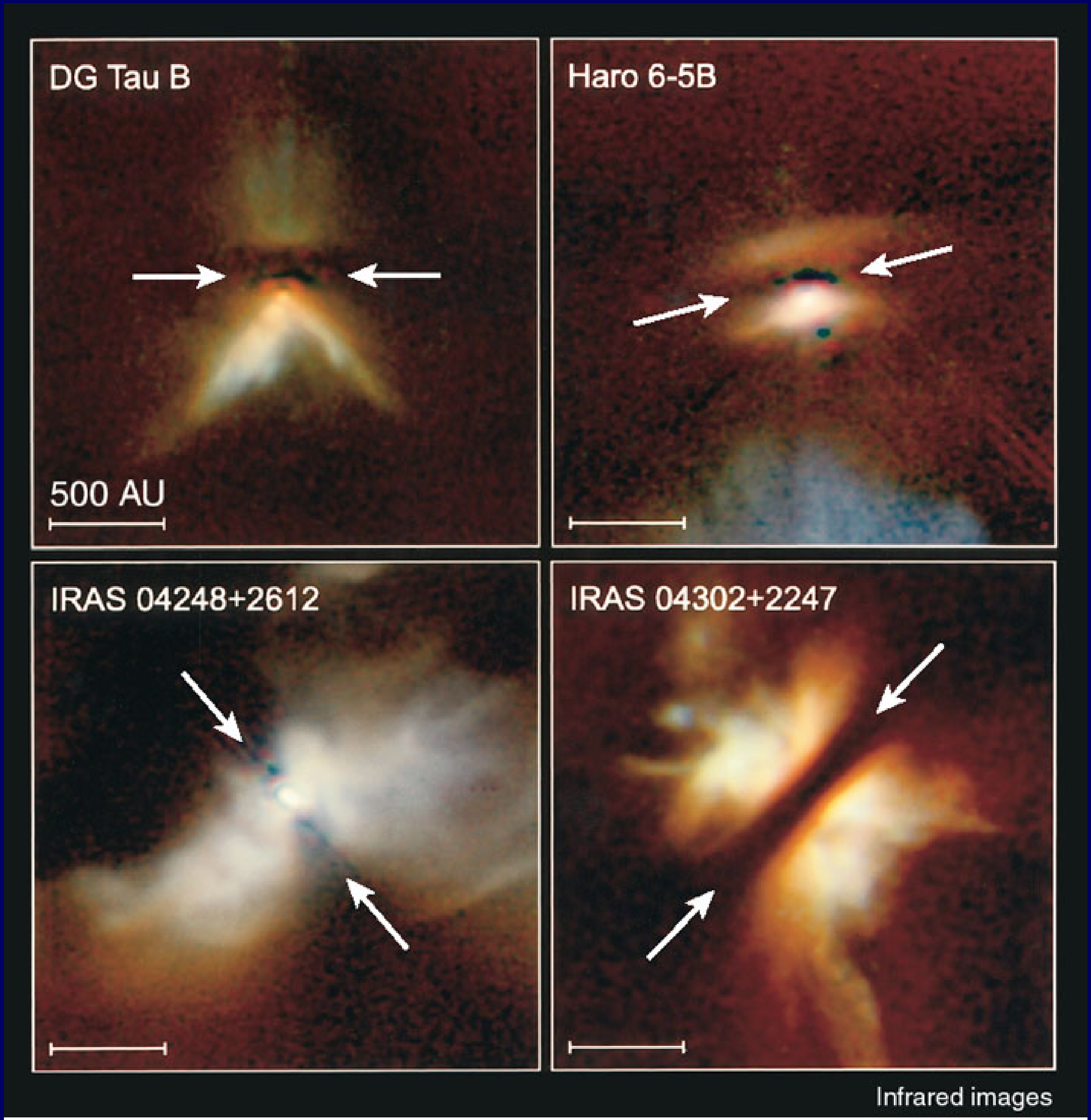
Evidence for Ongoing Planet Formation



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

Probably sites of planet formation right now!

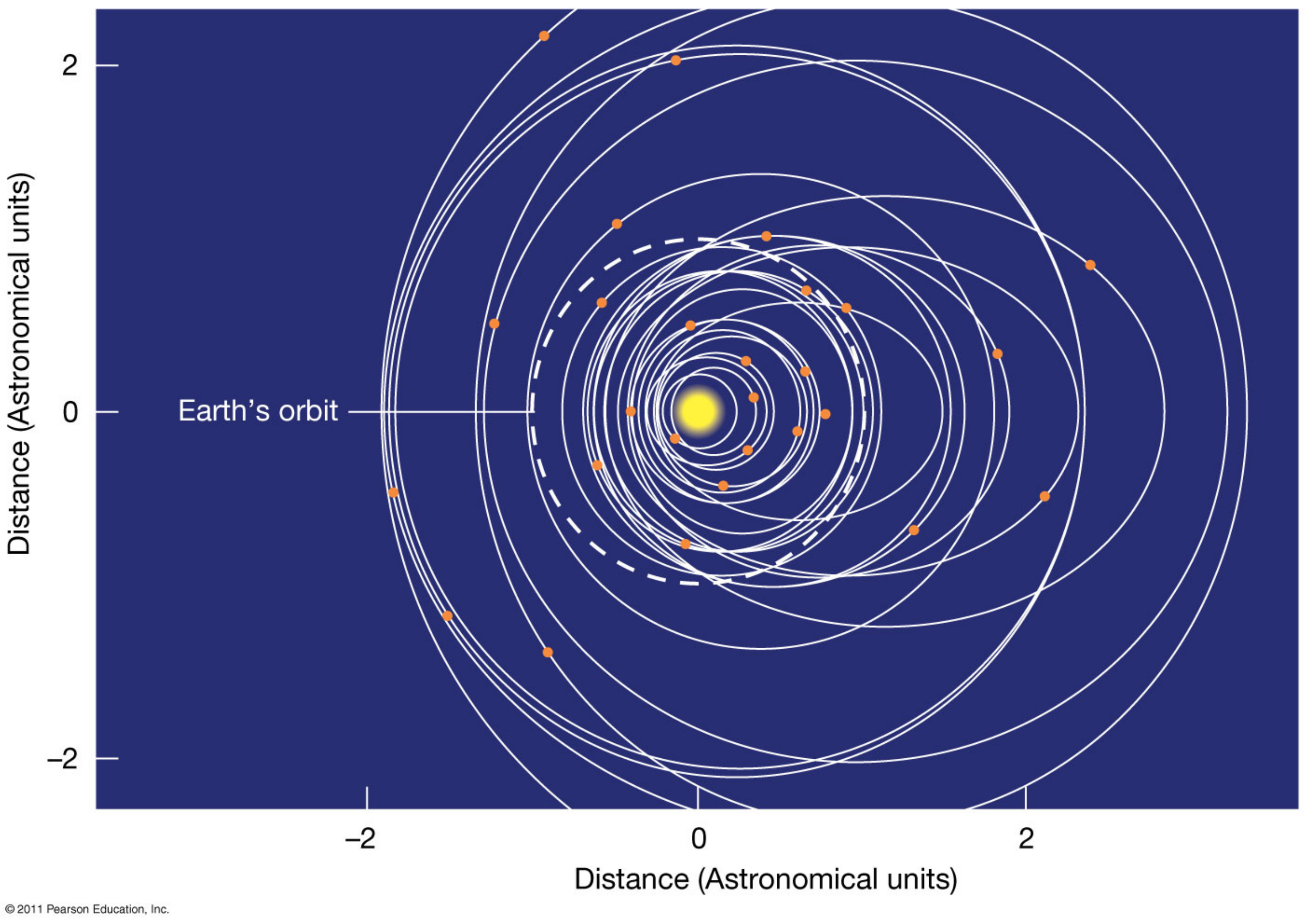
Dust Disks around Forming Stars



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

Planets of Other Stars

Orbits of 60 of the known extrasolar planets; note that some of them are very close to their star.



Planets of Other Stars

Planets orbiting within 0.1 A.U. of their stars are called "hot Jupiters"; they are not included in the previous figure but are numerous.

Stars with composition like our Sun are much more likely to have planets, showing that the "dusty disk" theory of solar system formation is plausible.

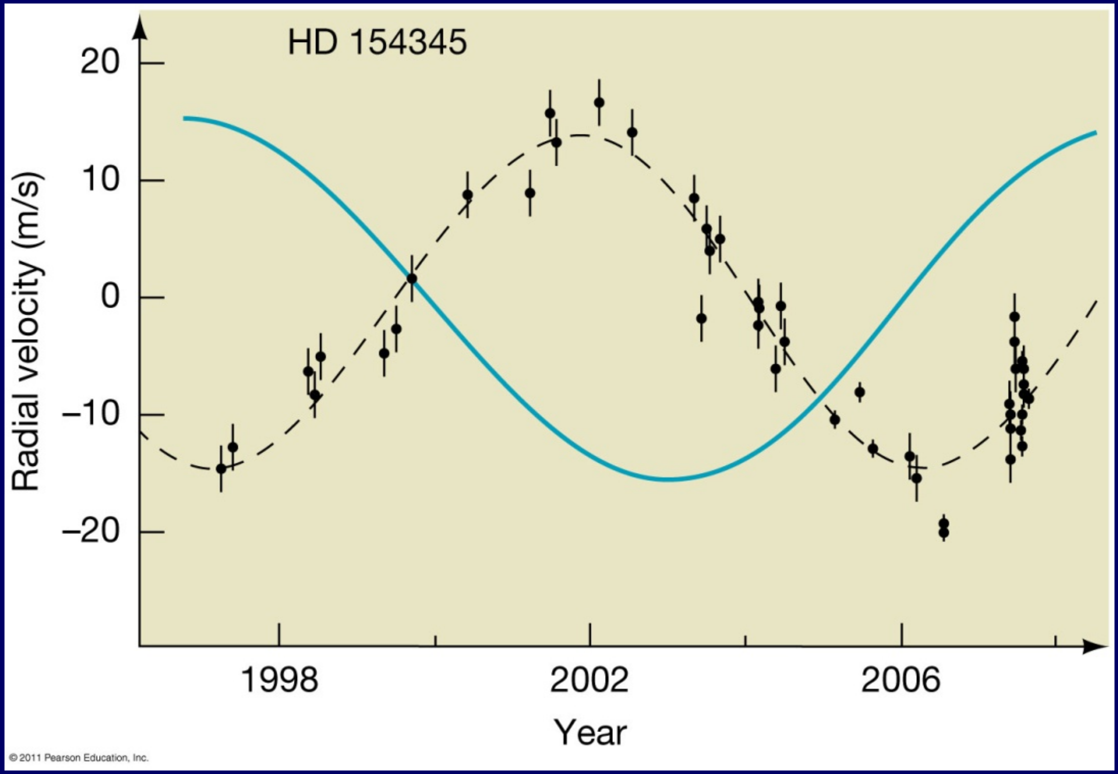
Some of these "planets" may actually be brown dwarfs (*i.e.* a large body not quite large enough to be a star), but probably not many.

The other planetary systems discovered so far appear to be very different from our own. Selection effect biases sample toward massive planets orbiting close to parent star; lower-mass planets cannot be detected this way.

Planets of Other Stars

Recently, more Jupiter-like planets have been found; this one has almost the mass of Jupiter and an orbital period of 9.1 years.

The blue line is the same curve for Jupiter.



Planets of Other Stars

This figure shows the size of the habitable zone (where there is a possibility of liquid water being present) as a function of the mass of the parent star. Gliese 581c and Gliese 581d are close to this zone.