

# Comparative Planetology II: The Origin of Our Solar System

ATL Microscopical

HD 107146

(direct face-on)



Size of  
Neptune's  
Orbit

## Chapter Eight



Neptune's Orbit

# Introduction To Modern Astronomy I: Solar System

Introducing Astronomy  
(chap. 1-6)

Planets and Moons  
(chap. 7-15)

Chap. 16:  
Chap. 28:

Ch7: Comparative Planetology I

**Ch8: Comparative Planetology II:  
The Origin of Our Solar System**

Ch9: The Living Earth

Ch10: Our Barren Moon

Ch11: Earthlike Planets

Ch12: Jupiter and Saturn

Ch13: Satellites of Jupiter & Saturn

Ch14: Uranus, Neptune and Beyond

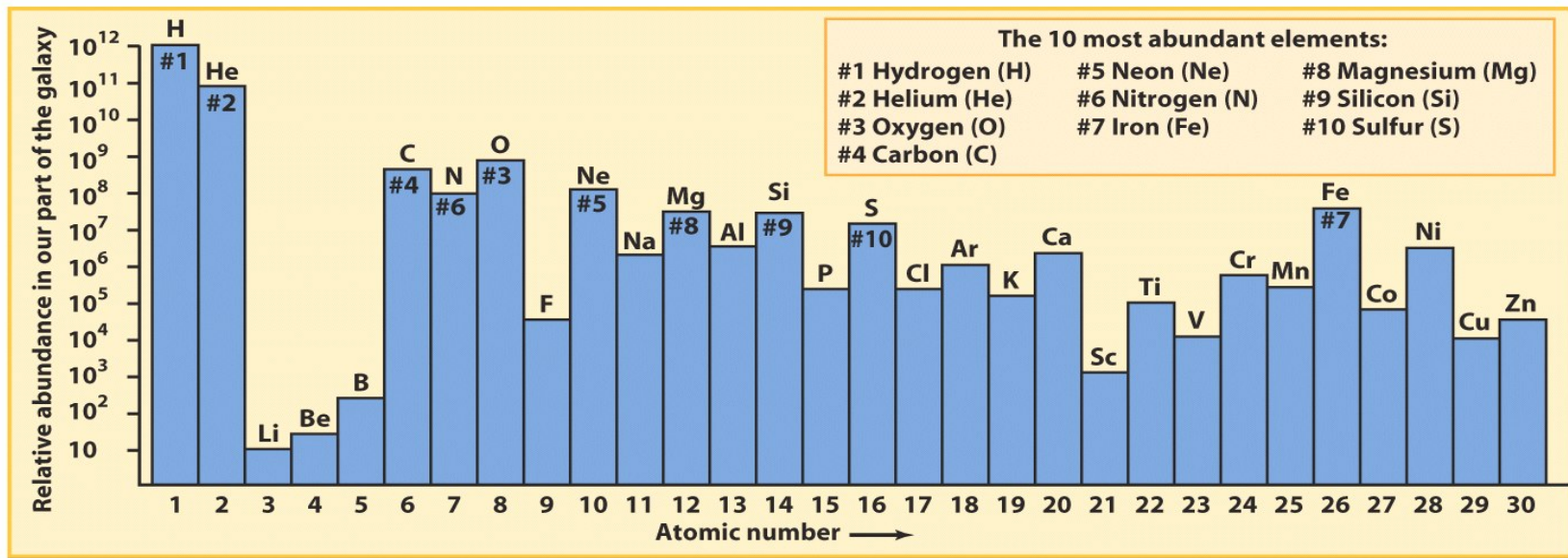
Ch15: Vagabonds of Solar System

# Constraints on Models

- Any theoretical models must be able to explain the observed properties of the present-day planets
  1. The terrestrial planets, which are composed primarily of rocky substances, are relatively small, while the Jovian planets, which are composed primarily of hydrogen and helium, are relatively large
  2. All of the planets orbit the Sun in the same direction, and all of their orbits are in nearly the same plane
  3. The terrestrial planets orbit close to the Sun, while the Jovian planets orbit far from the Sun

# Origin of Chemical Elements

- Composition of the solar system (by mass)
  - Dominated by hydrogen (H, 71%) and helium (He, 27%)
  - All other chemical elements, combined, make up the remaining 2%, e.g., oxygen (O), carbon (C), nitrogen (N), Iron (Fe), silicon (Si).
  - For each  $10^{12}$  H atoms,  $10^{11}$  He,  $8.5 \times 10^8$  O, 6 gold atom



Abundances in the Solar System (by number)

# Origin of Chemical Elements

- **Hydrogen and helium atoms were produced in the Big Bang that happened 13.7 billion years ago.**
- **All heavier elements were manufactured by stars later.**
  - Thermal-nuclear fusion reaction in the interior of stars
  - Supernova explosions.
- As it dies, a star ejects a large amount of material containing heavy elements into the **interstellar medium**
- New stars form from the enriched interstellar medium, and have the similar abundance as the interstellar medium.
- Solar system contains “recycled” heavy elements from stars that died long ago.

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# The age of Solar System

- The solar system is believed to be about **4.56 billion years old**
- Radioactive dating is used to determine the ages of rocks
  - Radioactive elements decay into other elements or isotopes
  - The decay rate, measured in **half life**, is constant for radioactive element.
    - e.g., Carbon 14 (-> Nitrogen 14): 5730 years;
    - e.g., Uranium 238 (-> Lead 206): 4.5 billion year
  - By measuring the numbers of the radioactive elements and the newly-created elements by the decay, one can calculate the age

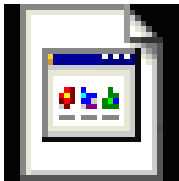
# The age of Solar System

- All Meteorites show nearly the *same* age, about 4.56 billion years.
  - Meteorites are the oldest rocks found anywhere in the solar system
  - They are the bits of **meteoroids** that survive passing through the Earth's atmosphere and land on our planet's surface
- On the Earth, most rocks are only hundreds of millions of years old.
- Moon rocks are also about 4.5 billion years old



# Solar Nebula Hypothesis

- Hypothesis: the Sun and planets formed from a common **solar nebula**.
- **Solar nebula** is a **vast, rotating cloud of gas and dust** in the interstellar space
- It is so far the most successful model of the origin of the solar system.



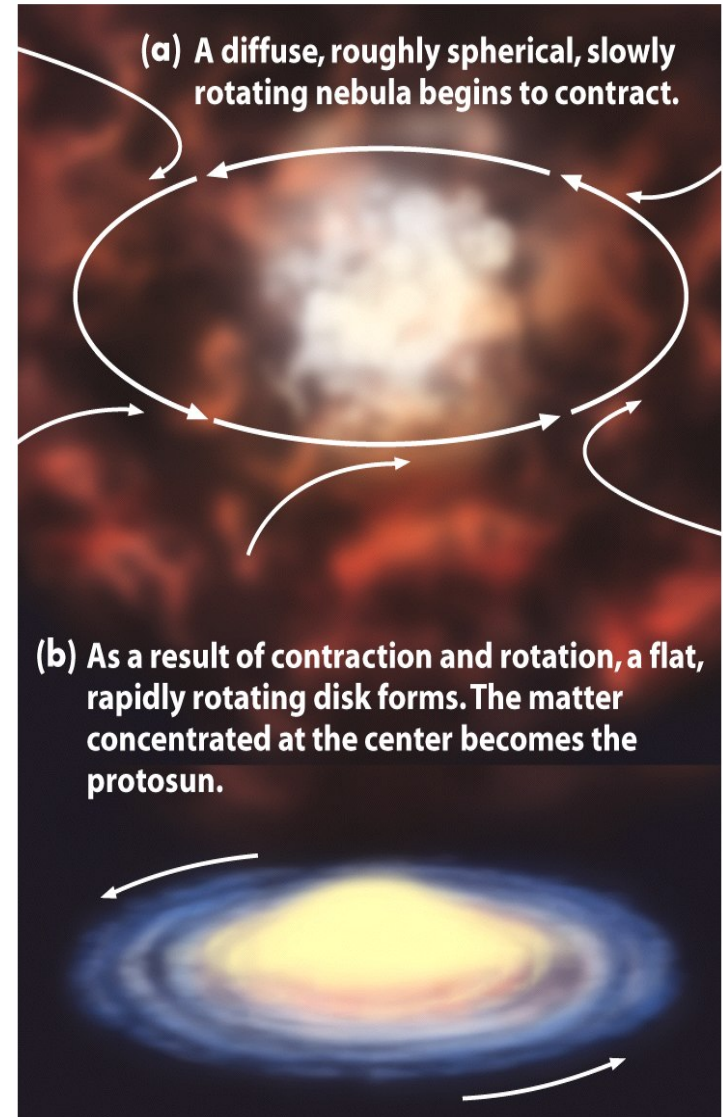
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**FLASH**

A common rotating cloud explains why all planets orbit the Sun in the same direction.

# Solar Nebula Hypothesis

- The nebula began to contract about 4.5 billion years ago, under its own gravity
- **Protosun:** as it contracted, the greatest concentration occurred at the center of the nebula, forming a relatively dense region called the **protosun**
- The protosun' temperature continued to climb, because of the **conversion of gravitational energy into thermal energy**
- Eventually (~10 million years), the center temperature reached ~ 2 million Kelvin, and nuclear reaction ignited, and contraction stopped.
- Nuclear reactions continue to the present day in the interior of the Sun.



# Solar Nebula Hypothesis

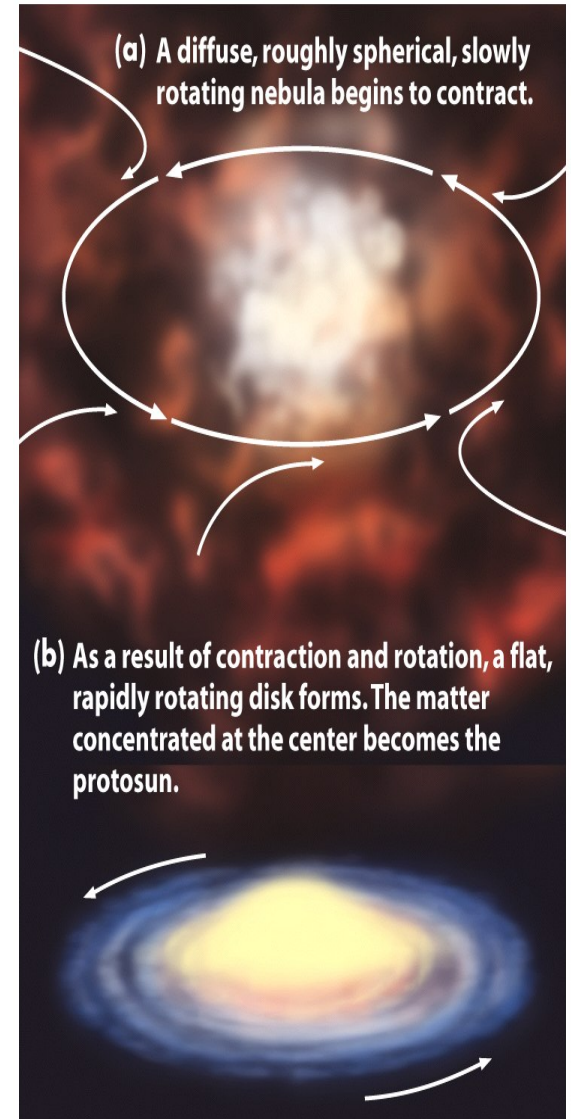
- **Protoplanetary disk:** As it contracted, the cloud flattened and spun more rapidly around its rotation axis, forming a disk surrounding the protosun.
- It spun faster because of the conservation of angular momentum



(a)



(b)

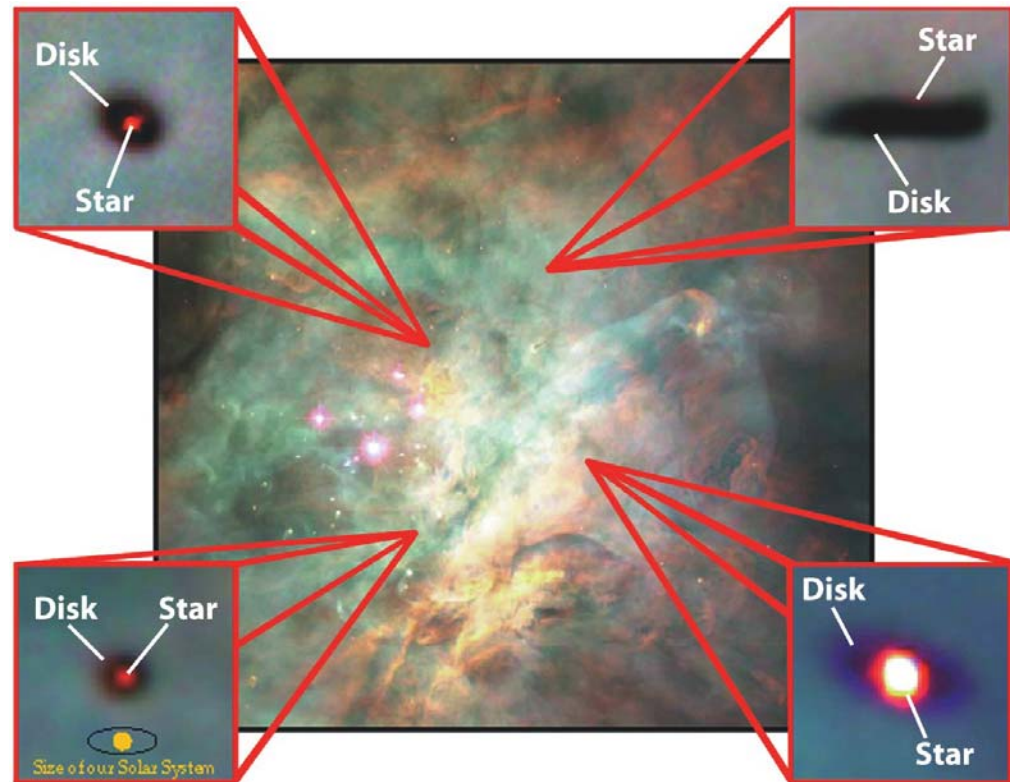


(a) A diffuse, roughly spherical, slowly rotating nebula begins to contract.

(b) As a result of contraction and rotation, a flat, rapidly rotating disk forms. The matter concentrated at the center becomes the protosun.

# Solar Nebula Hypothesis

- The flattened disk is also an effect of the rotation of the nebula.
- The centrifugal force of the rotation slows down the material on the plane perpendicular to the rotational axis fall toward the center
- But the centrifugal force has no effect on the contraction along the rotational axis



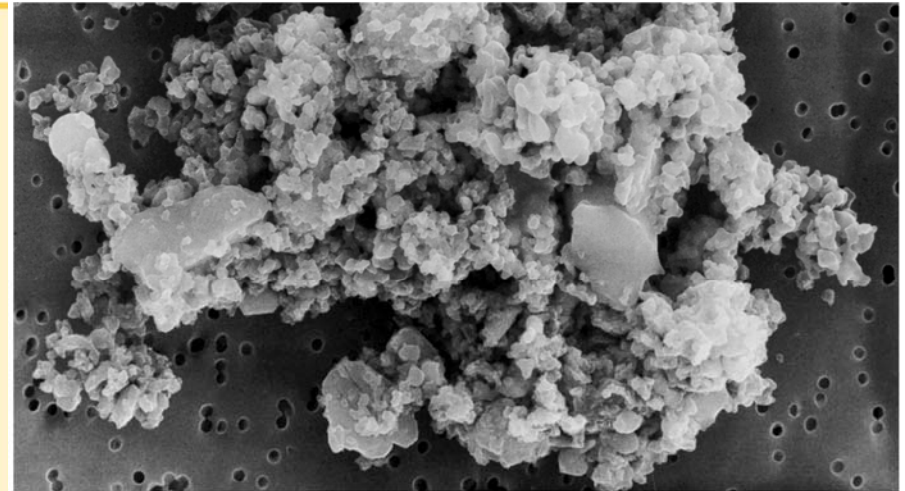
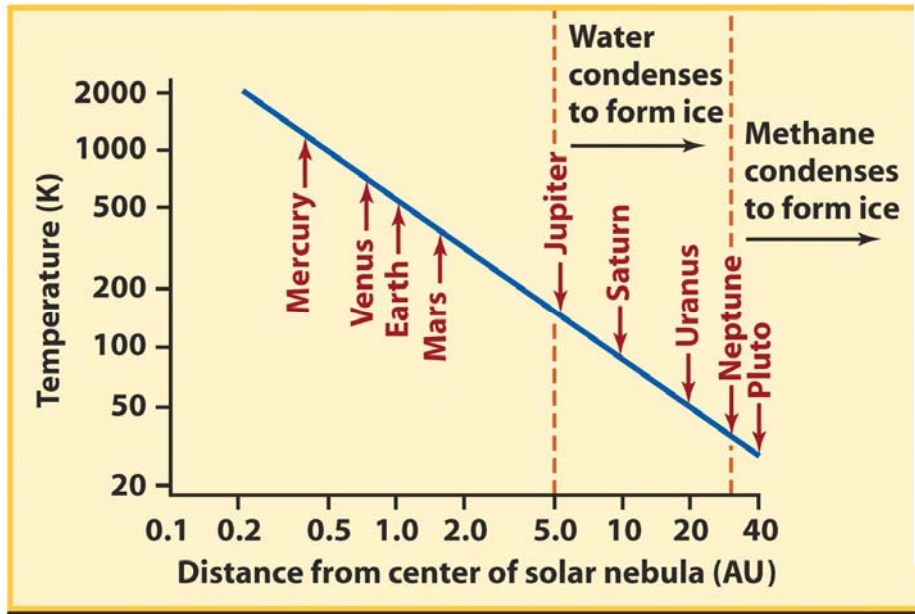
Proto-stars and Proto-planetary disks in Orion Nebula

# Formation of Planets

- A substance is in the state of either solid or gas, but not in liquid, if the pressure is low, such as in the atmosphere
- **Condensation temperature** determines whether a certain substance is a solid or a gas.
  - Above the condensation temperature, gas state
  - Below the condensation temperature, solid state
- Hydrogen and Helium: always in gas state, because condensation temperatures close to absolute zero
- Substances such as **water (H<sub>2</sub>O)**, **methane (CH<sub>4</sub>)** and **ammonia (NH<sub>3</sub>)** have low condensation temperature, ranging from 100 K to 300 K
  - In solid state, they form **ice particles**
- Rock-forming substances have condensation temperatures from 1300 K to 1600 K
  - Through collision and merge, they form **dust grain**

# Formation of Planets

- In the nebula, temperature decreases with increasing distance from the center of the nebula
- In the inner region, only heavy elements and their oxygen compounds remain solid, e.g., iron, silicon, magnesium, sulfur. They form dust grains.
- In the outer region, ice particles were able to survive.

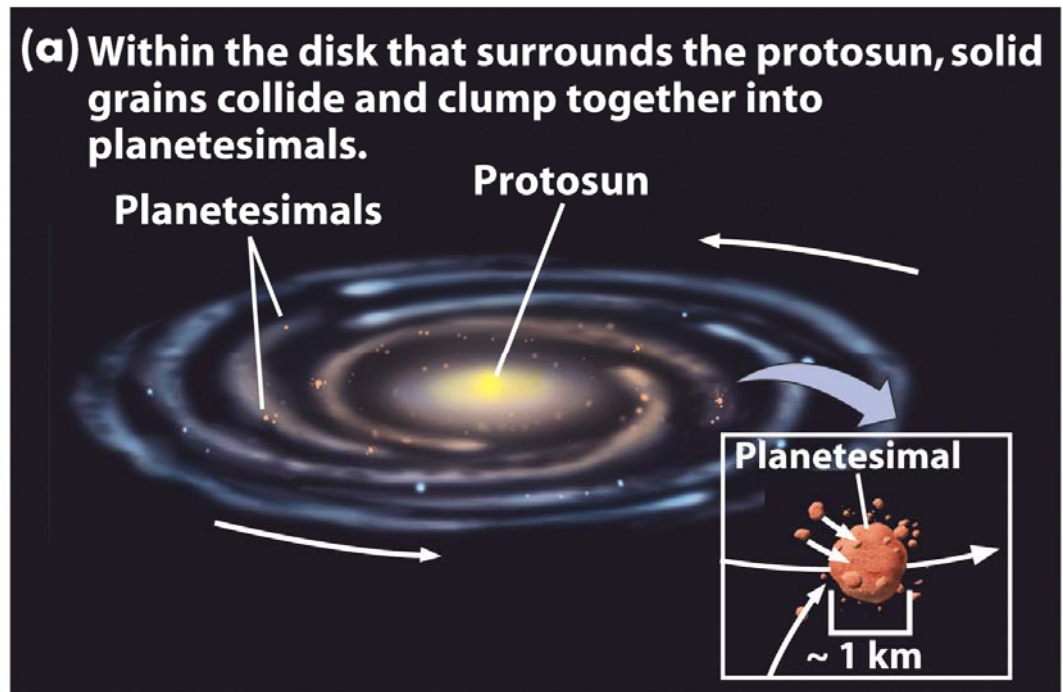


10  $\mu\text{m}$  = 0.01 mm

**Dust grain**

# Formation of Terrestrial Planets

- In the inner region, the collisions between neighboring dust grains formed small chunks of solid material
- **Planetesimals:** over a few million years, these small chunks coalesced into roughly a billion asteroid-like objects called planetesimals
- **Planetesimals** have a typical diameter of a kilometer or so

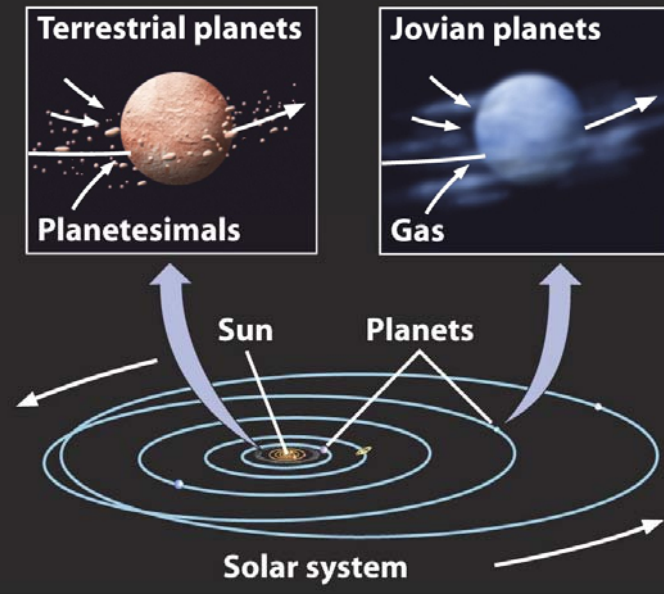


# Formation of Terrestrial Planets

- **Protoplanets:** gravitational attraction between the planetesimals caused them to collide and accumulate into still-larger objects called protoplanets
- Protoplanets were roughly the size and mass of our Moon
- During the final stage, the **protoplanets collided to form the terrestrial planets**

Terrestrial planets are solid because they are made of solid dust grains

(b) The terrestrial planets built up by collisions and by the accretion of planetesimals by gravitational attraction. The Jovian planets formed by gas accretion.





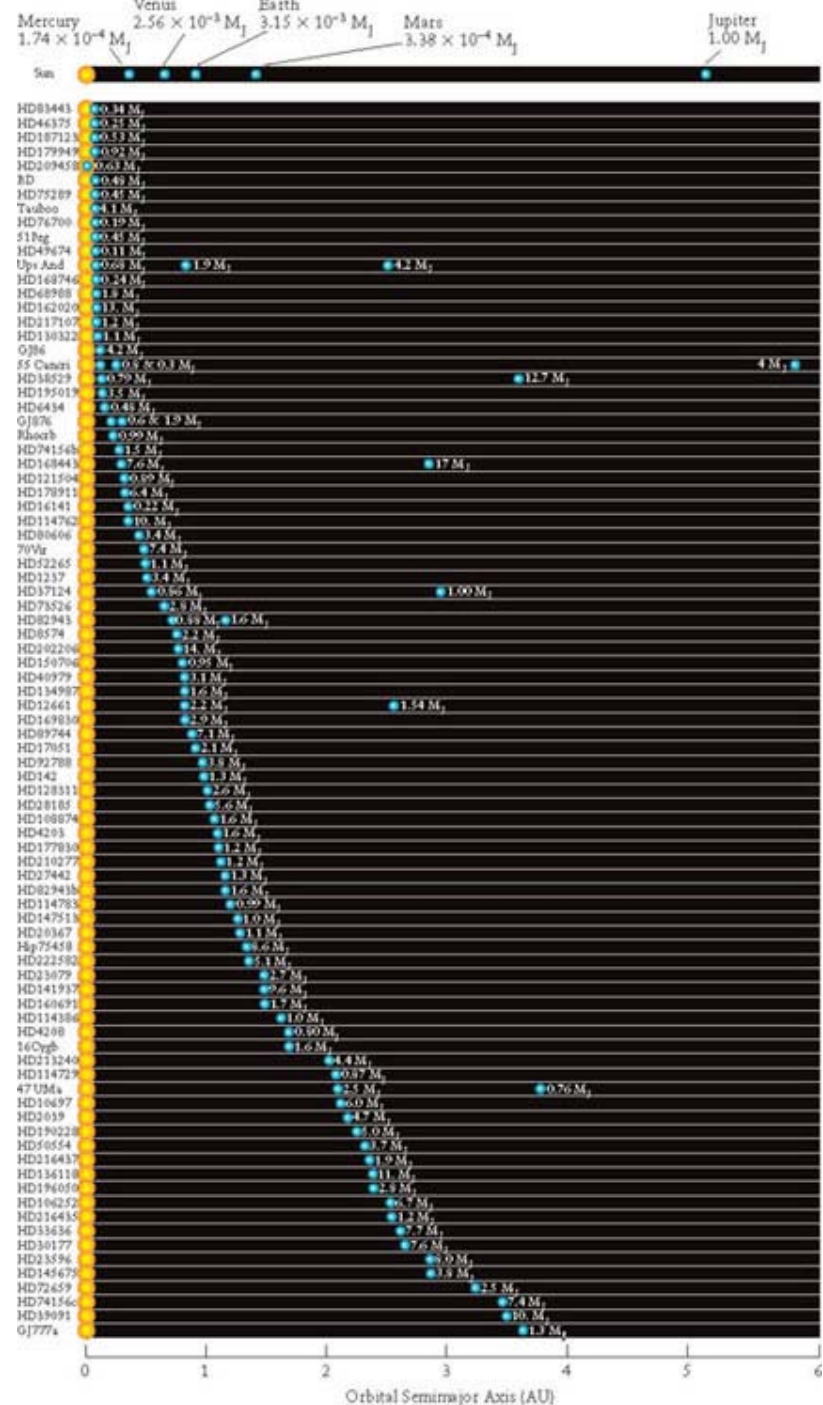
# Formation of Jovian Planets

- In the outer region, more solid materials were available to form planetesimals.
  - Planetesimals were made of a mixture of ices and rocky materials, which could become bigger
- Protoplanets could have captured an envelope of gas
  - Gas atoms, hydrogen and helium, were moving slowly in the outer region and so easily captured by the gravity of the massive cores.
  - this is called **core accretion model**
- The result was a huge planet with an enormously thick, hydrogen-rich envelope surrounding a rocky core with 5-10 times the mass of the Earth

Jovian planets are gaseous because of the capture of gases. They are large because of taking both dust grains and ices

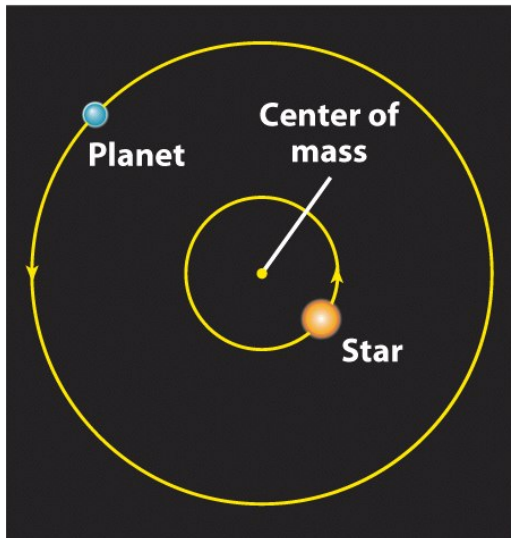
# Extrasolar Planets

- In 1995, the first extrasolar planet was discovered.
- As of Oct. 22, 2006, 199 extrasolar planets have been found
- As of Oct 20. 2007, 257 extrasolar planets have been found

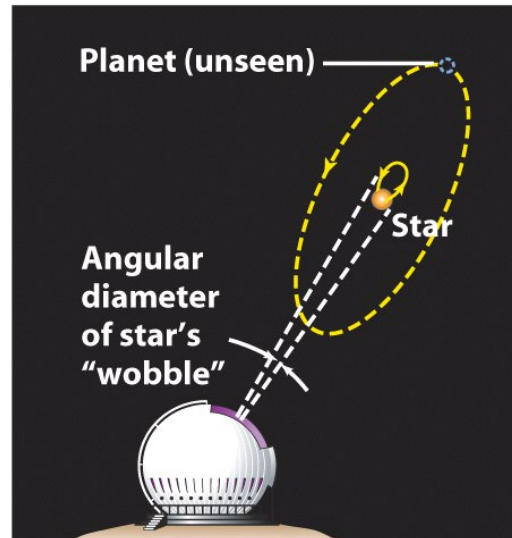


# Extrasolar Planets

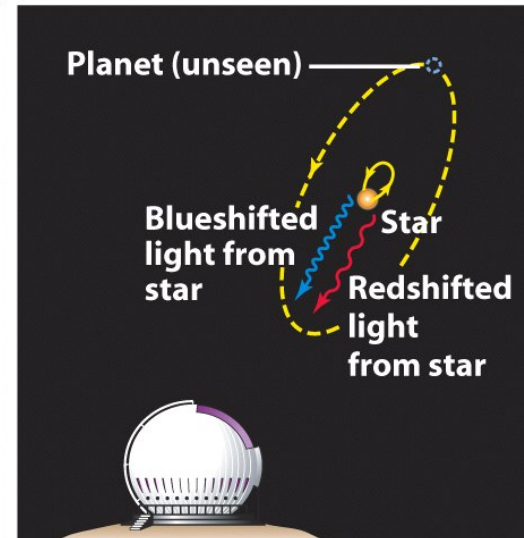
- Extrasolar planets can not be directly observed, because their reflected light is about 1 billion times dimmer than that of their parent stars
- Their presence is detected by the “**wobble**” of the stars
- The “wobble” motion of star is caused by the gravitational force of the planets
- The “wobble” motion can be detected using Doppler effect.



(a) A star and its planet



(b) The astrometric method



(c) The radial velocity method

# Final Notes on Chap. 8

- All 7 sections are covered.

# Advanced Question

## Chap. 8, Q31 in P206

Three-quarters of the radioactive potassium ( $^{40}\text{K}$ ) originally contained in a certain volcanic rock has decayed into argon ( $^{40}\text{Ar}$ ). How long ago did this rock form?