

Astronomy

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Small 239

Office hours:

MTWR 10-11am

Planetology II

- Key characteristics
- Chemical elements and planet size
- Radioactive dating
- Solar system formation
- Solar nebula and planet formation
- Terrestrial planet formation
- Jovian planet formation
- Exoplanets

Key Properties of the Solar System

TABLE 8-1 Three Key Properties of Our Solar System

Any theory of the origin of the solar system must be able to account for these properties of the planets.

<i>Property 1: Sizes and compositions of terrestrial planets versus Jovian planets</i>	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 (see Sections 7-1 and 7-4).
<i>Property 2: Directions and orientations of planetary orbits</i>	All of the planets orbit the Sun in the same direction, and all of their orbits are in nearly the same plane (see Section 7-1).
<i>Property 3: Sizes of terrestrial planet orbits versus Jovian planet orbits</i>	The terrestrial planets orbit close to the Sun, while the Jovian planets orbit far from the Sun orbits versus Jovian planet orbits (see Section 7-1).

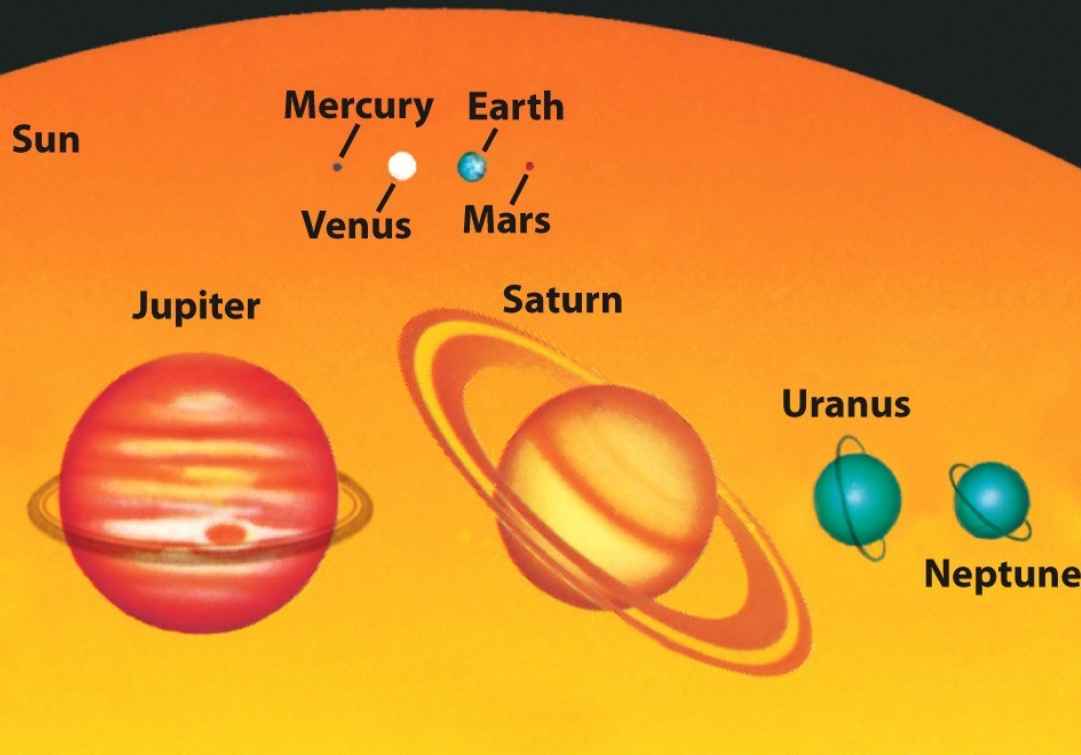
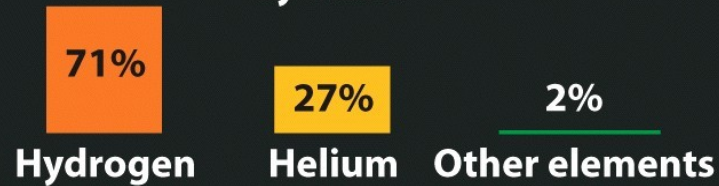
Table 8-1

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Cosmic Abundance of Chemical Elements

Composition of the solar system
(Sun, planets, and small bodies)
by mass:



The 'Big Bang' that created the universe created mainly hydrogen with small amounts of He and Li

Hydrogen and helium comprise 71% and 27% respectively of the universe by mass. All the other elements from lithium to uranium make up only 2% of the universe. Both the solar system and the entire universe have the same composition.

Figure 8-1
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Cosmic Abundance of Chemical Elements

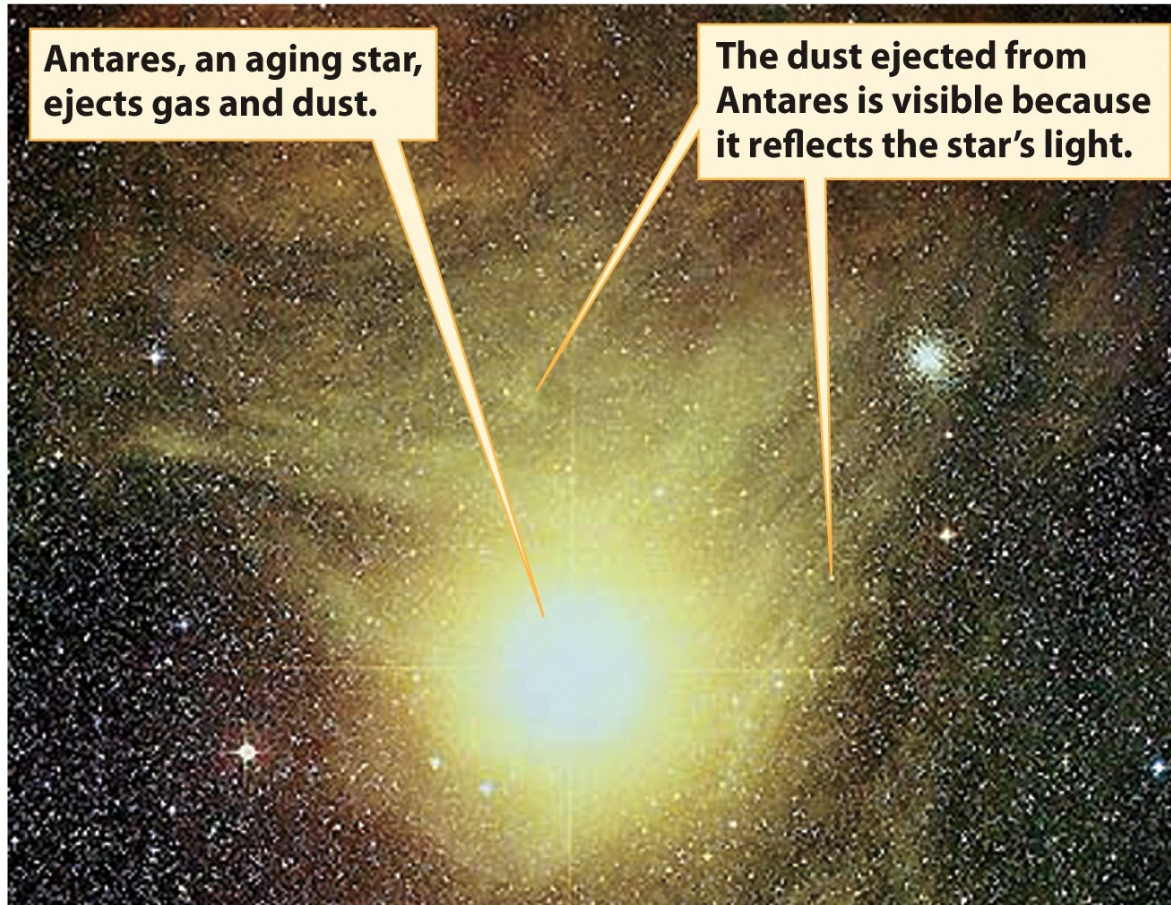
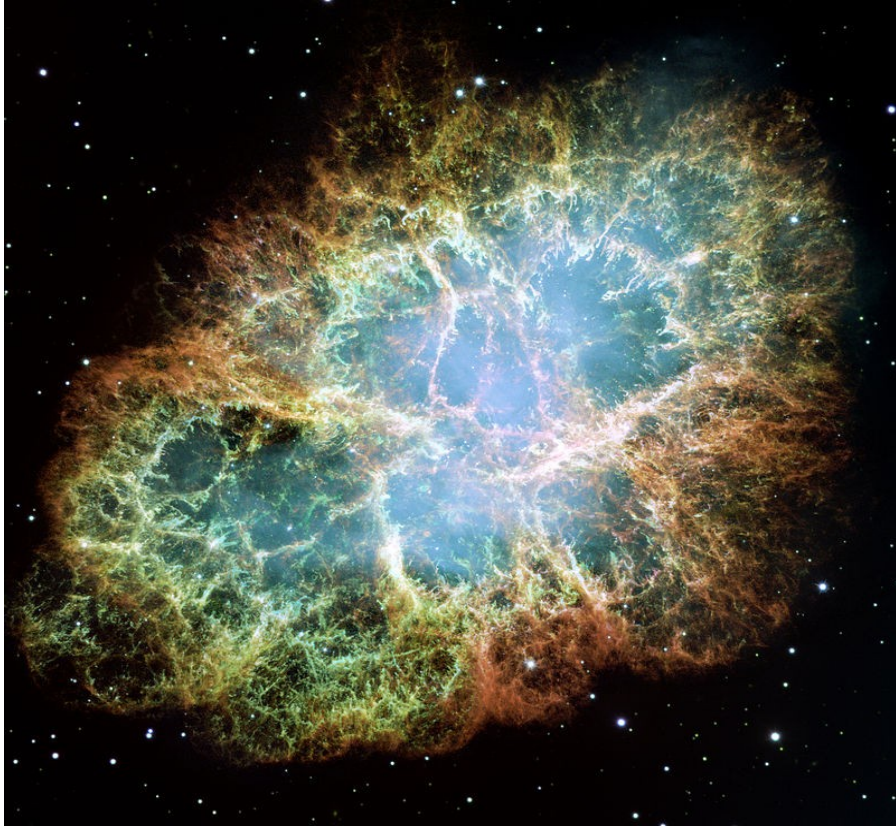


Figure 8-2
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David Malin/Anglo-Australian Observatory

Stars 'burn' hydrogen into He and other light elements. As stars age, they eject particles out into space. These dust particles contain the lighter elements up to iron (Fe). The lighter elements are spread throughout the interstellar medium.

Cosmic Abundance of Chemical Elements



Some massive stars explode in a **supernova** at the end of their lives. Supernovas produce all the elements heavier than iron (Fe) up to uranium (U). These elements are dispersed into the interstellar medium from supernovas.

This image is of a supernova that exploded in 1054. The remnants of the explosion are the Crab nebula.

Cosmic Abundance of Chemical Elements

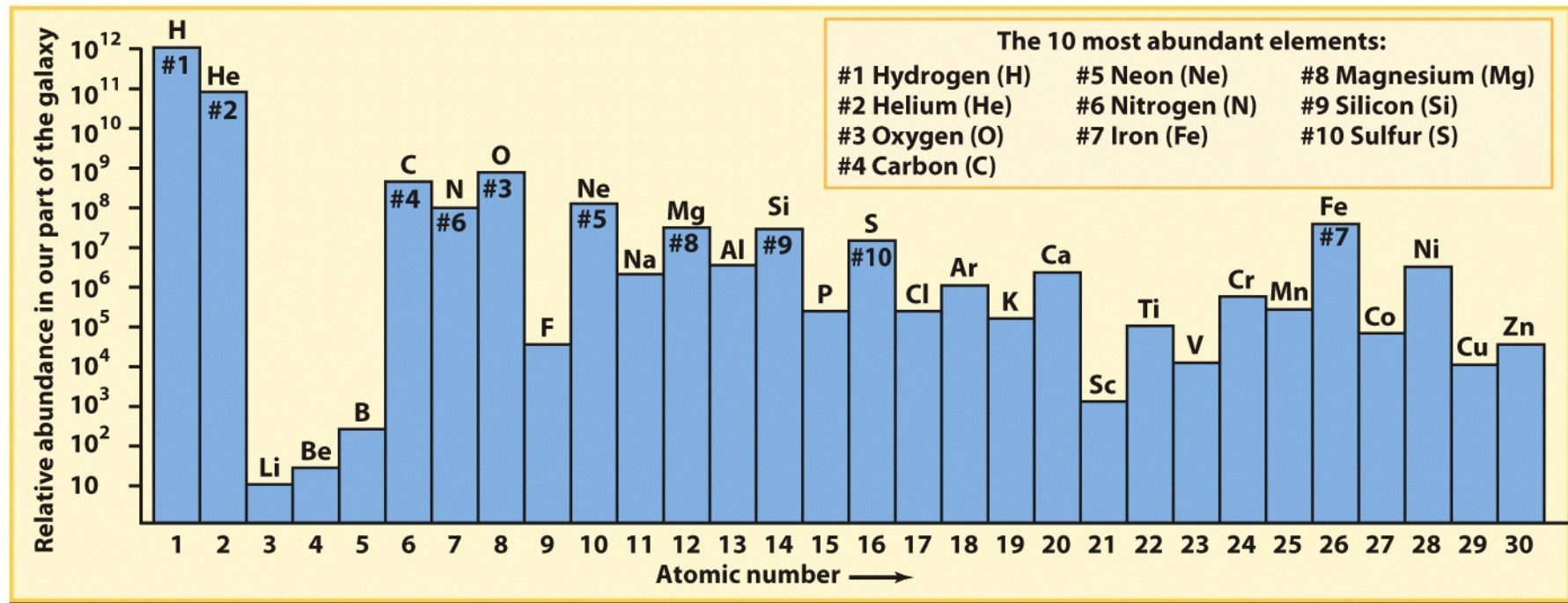


Figure 8-4

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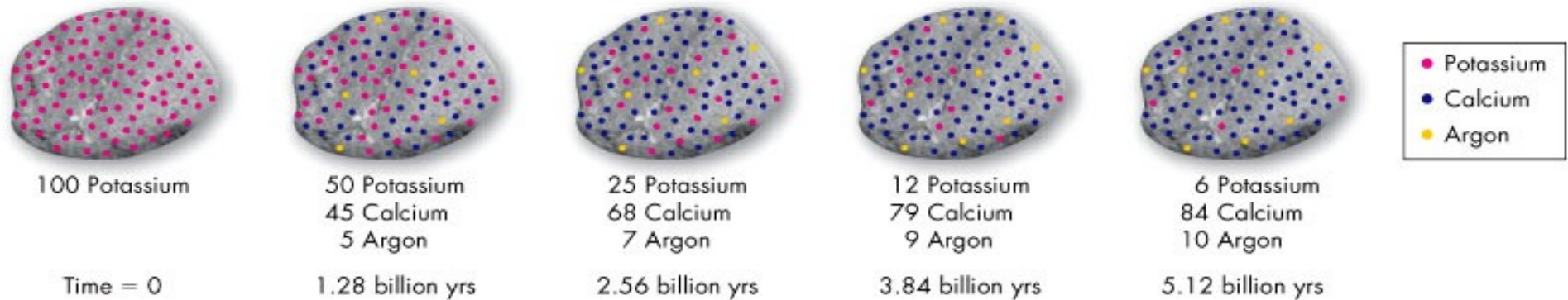
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Note the log scale on the vertical axis

Different elements are made in different ways in the fusion (burning) process in stars and in supernova explosions. The abundance of H and He explains why the Jovian planets are large while the rarity of elements like Si, Al, Na and C explain why the terrestrial planets are small.

How Old is the Solar System? Radioactive Dating

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- Some atoms that occur naturally are not stable
- They eventually decay into other types of atoms
 - > Radioactive atoms decay into **daughter atoms**
 - > For instance, radioactive Potassium decays into daughter atoms Calcium and Argon
 - > Rate of radioactive decay is constant, and provides a natural clock.

Radioactive Dating

Original Radioactive Isotope	Final Stable Isotope	Half-Life (Years)	Range of Ages that Can Be Determined (Years)
Rubidium (^{87}Rb)	Strontium (^{87}Sr)	47.0 billion	10 million–4.54 billion
Uranium (^{238}U)	Lead (^{206}Pb)	4.5 billion	10 million–4.54 billion
Potassium (^{40}K)	Argon (^{40}Ar)	1.3 billion	50,000–4.54 billion
Carbon (^{14}C)	Nitrogen (^{14}N)	5730	100–70,000

Box 8-1 Table 1

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Different radioactive isotopes can be used to date time periods. ^{40}K and ^{238}U can date rocks to billions of years.



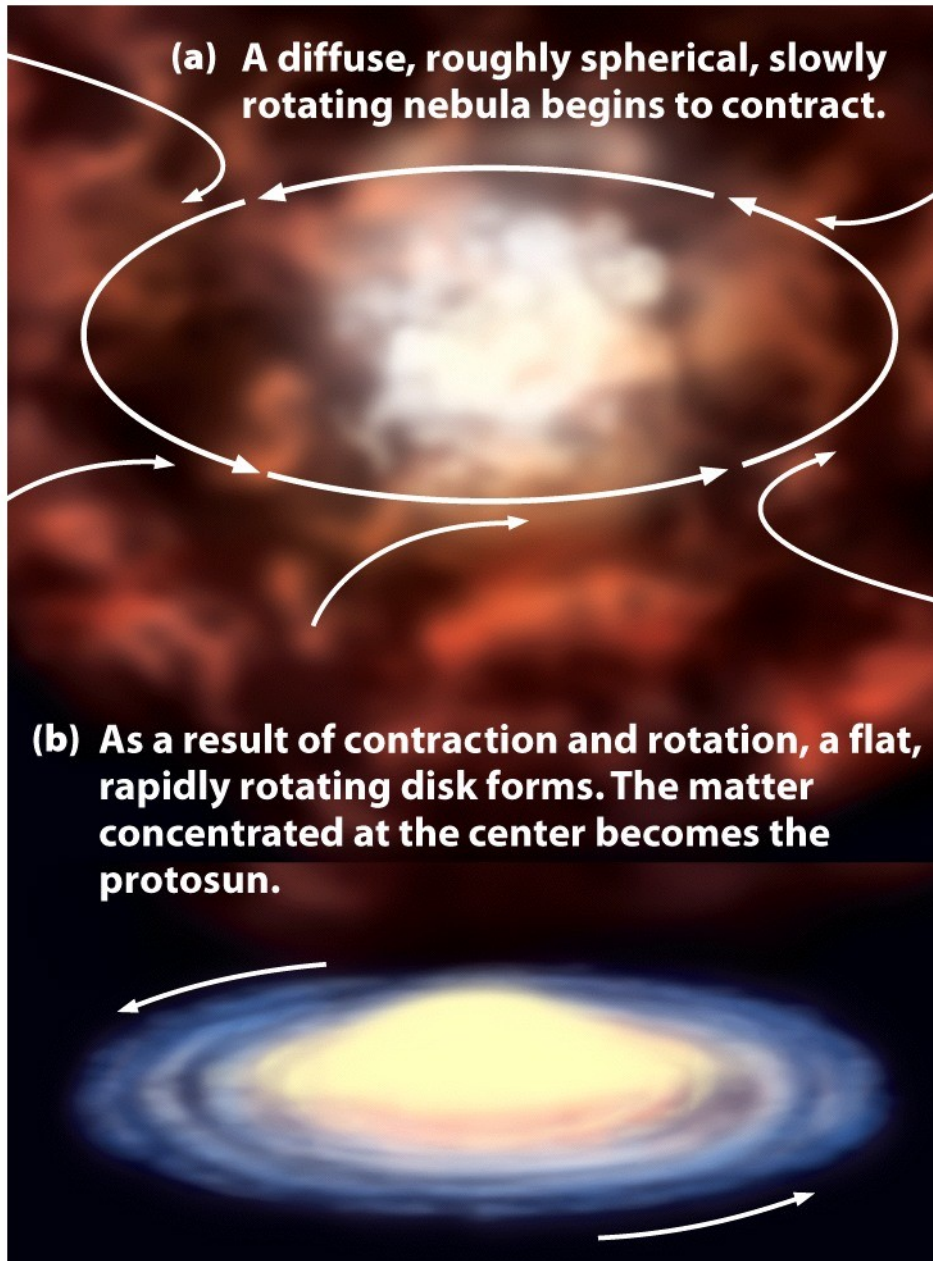
Figure 8-5
Universe, Tenth Edition
Tedd Simma/Photo Researchers, Inc.

The oldest rocks found on the Earth and Moon are about 4 billion years old. These are from when the Earth's surface cooled enough to be solid. Meteorites (small parts of asteroids that fall to earth) are dated at 4.5 billion.

Meteorites are thought to be as old as the solar system

Nebular Hypothesis

The Birth of the Solar System



A spherical, rotating cloud of gas and dust collapses under the influence of gravity. The gas and dust pulls into a flattened rapidly rotating disk. The disk is rapidly rotating because of angular momentum conservation. In the center with the largest concentration of gas and dust is the protosun. The disk will eventually form the planets.

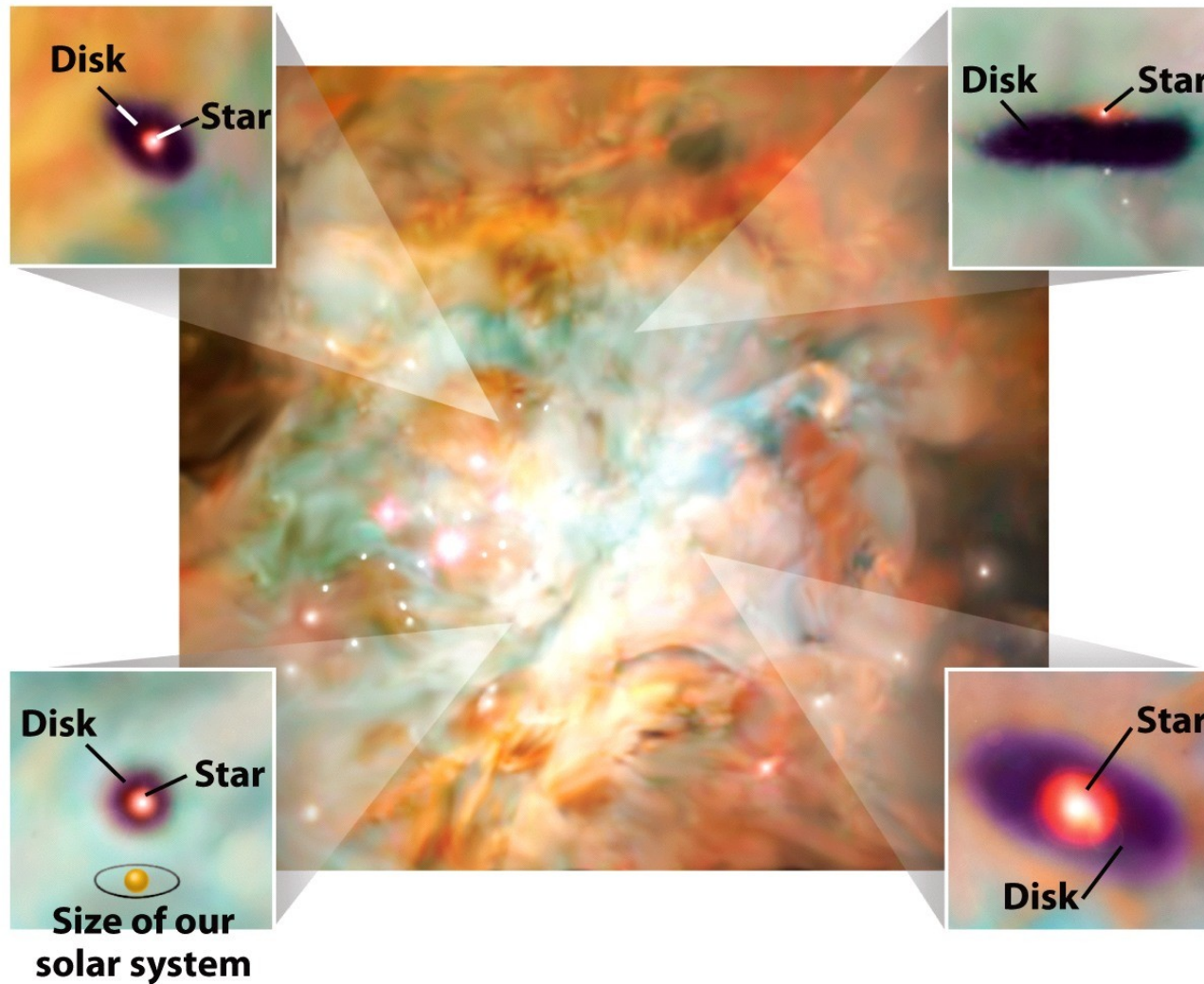
Nebular Hypothesis - Formation of the Sun



As the gas (mainly hydrogen) and dust continues to fall toward the center it heats up because gravitational potential energy is converted to kinetic energy. The kinetic energy of the colliding gas and dust is converted to heat. The

Protosun continues to contract and heat up until nuclear fusion occurs in the hydrogen. The fusion starts when the temperature reaches around 10 million Kelvin. This produces additional heat and pressure which eventually balance the contraction due to gravity.

Nebular Hypothesis - Formation of the Planets



When you look at regions where new stars are being born, you see the star surrounded by the protoplanetary disk. This Hubble image is a region in the Orion Nebula.

Figure 8-8b
Universe, Tenth Edition
C. R. O'Dell and S. K. Wong, Rice University; NASA

Nebular Hypothesis – Protoplanetary Disk

Before the protosun starts fusion and warms the protoplanetary disk, the low pressure and temperature cause small crystals of ice and other solid material to form small dust grains. Liquid water can not exist in these conditions.

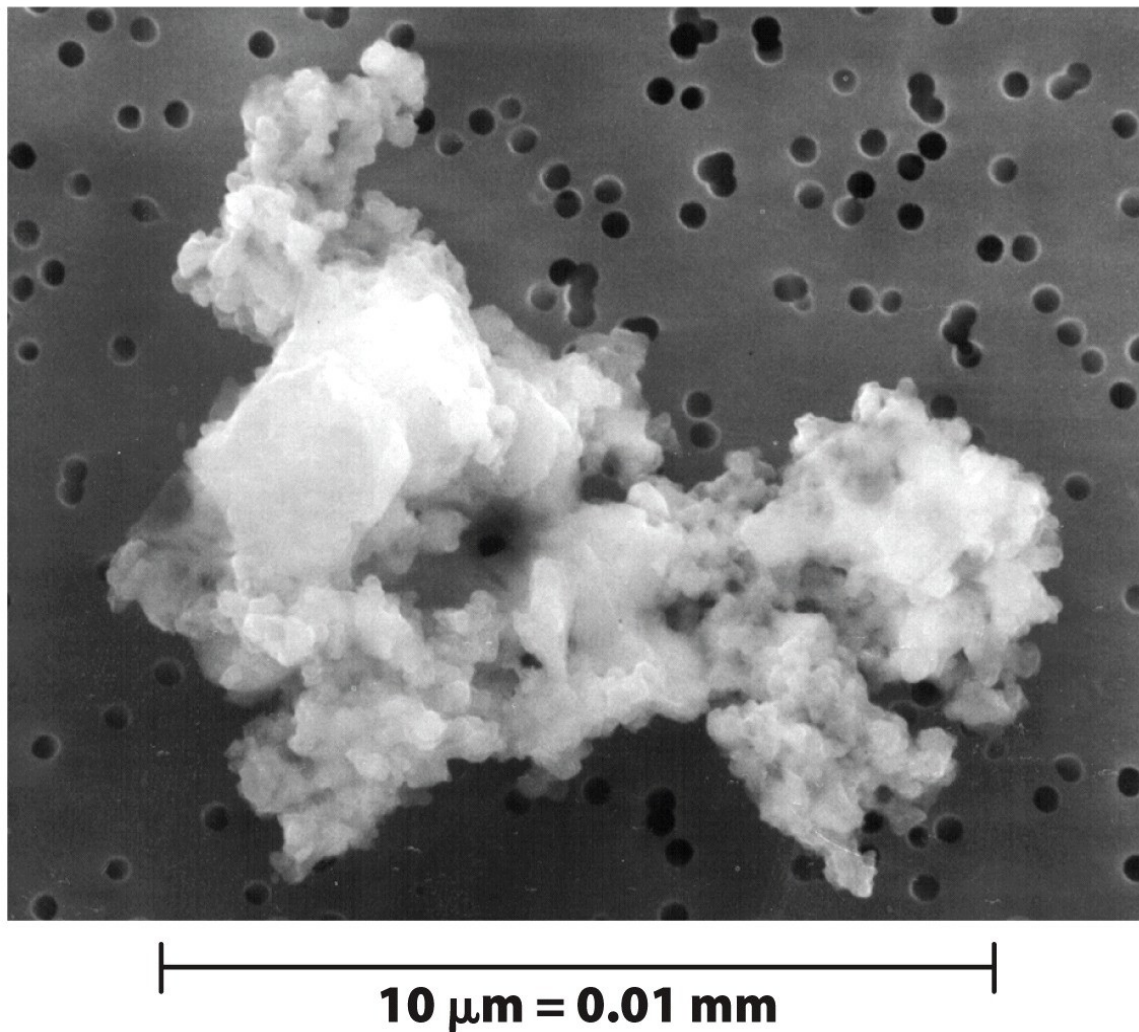
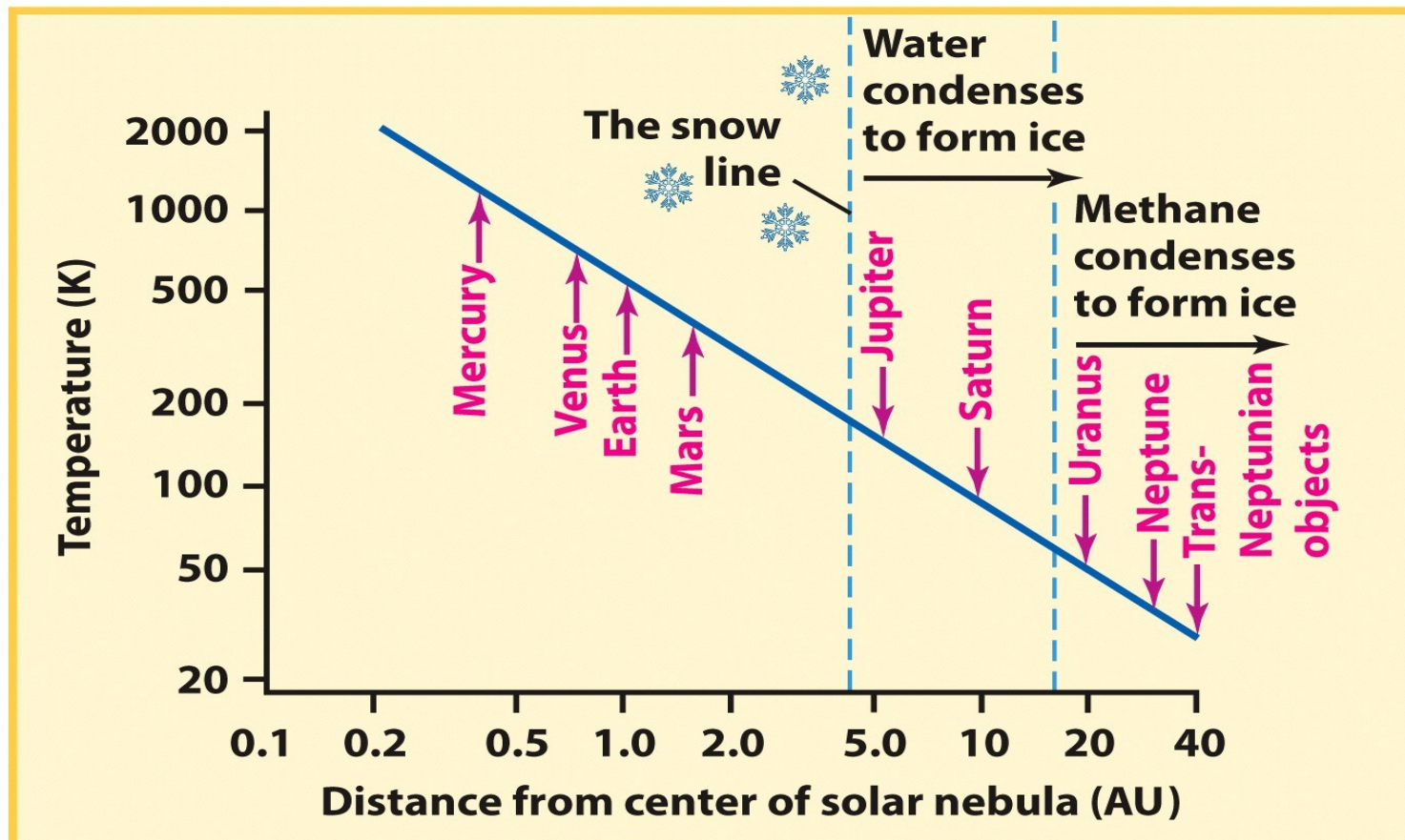


Figure 8-9
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NASA

The Snow Line in the Solar Nebula

As fusion in the protosun warms the protoplanetary disk, the water ice will melt and be dispersed leaving mainly rocky material like silicon compounds and metals like iron which do not melt in the higher temperatures. The melting line or 'snow line' is between the current location of Mars and Jupiter. Beyond the snow line water freezes into ice.

Between Saturn and Uranus, methane (CH_4) freezes into ice. Hydrogen and Helium do not freeze or condense at any temperature



Terrestrial and Jovian Planets

- In the warmer region inside of the snow line, the terrestrial planets (Mercury, Venus, Earth and Mars) form mainly out of rocky material and metals. Water, methane and ammonia (NH_3) remained a gas (or possibly a liquid)
- In the colder region outside of the snow line, water ice (and further out methane ice), hydrogen and helium form the Jovian planets.

Planetesimals and Protoplanets

The small dust grains of the protoplanetary disk collide over time and stick together under the influence of electric forces. Over millions of years these small object coalesce into billions of asteroid size planetesimal held together by gravity. These planetesimal collide and form protoplanets. Over hundreds of millions of years protoplanets form planets. Our Moon may have formed from one of the later collisions of a newly forming Earth with another large protoplanet.

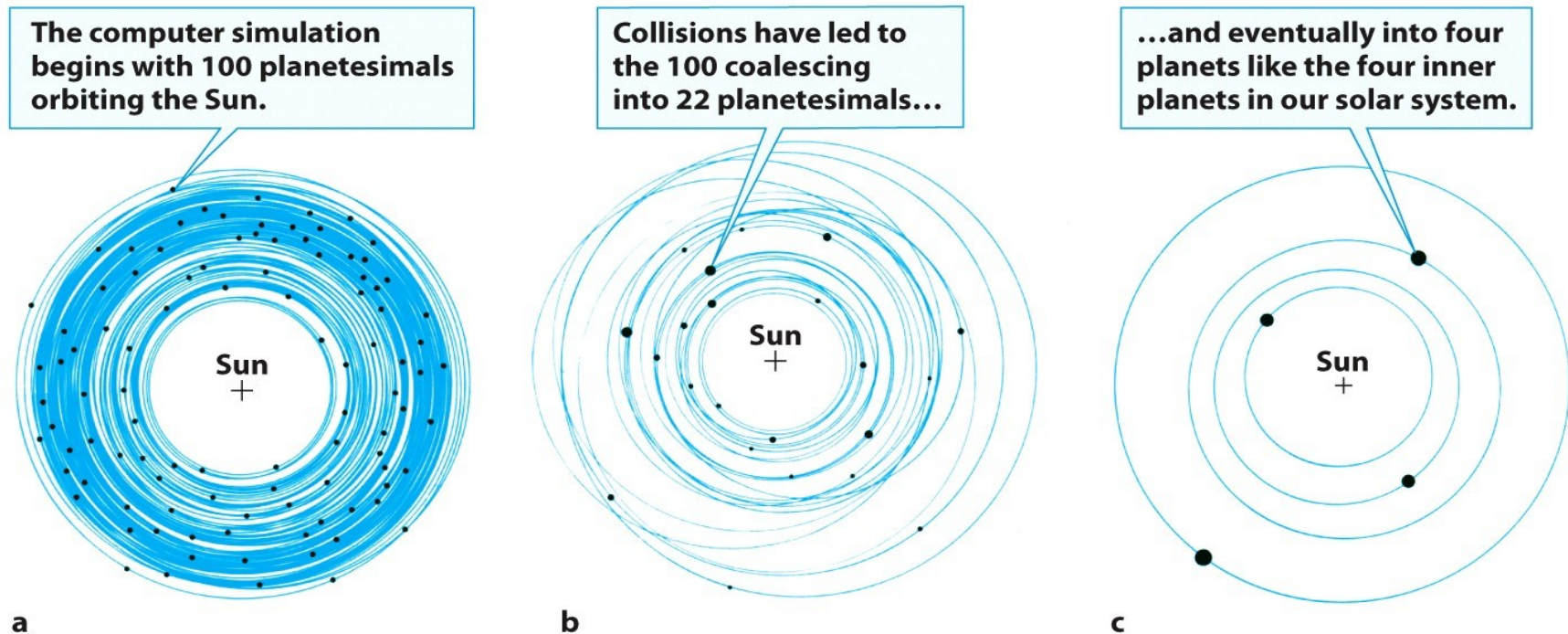


Figure 8-11

Formation of the Outer Solar System

Beyond the snow line there was more material because of the frozen ices. It is thought a large 'seed' Jupiter formed (~10 Earth masses). The gravity of the early Jupiter was large enough to capture H and He from the protoplanetary disk. This process is called the core accretion model.

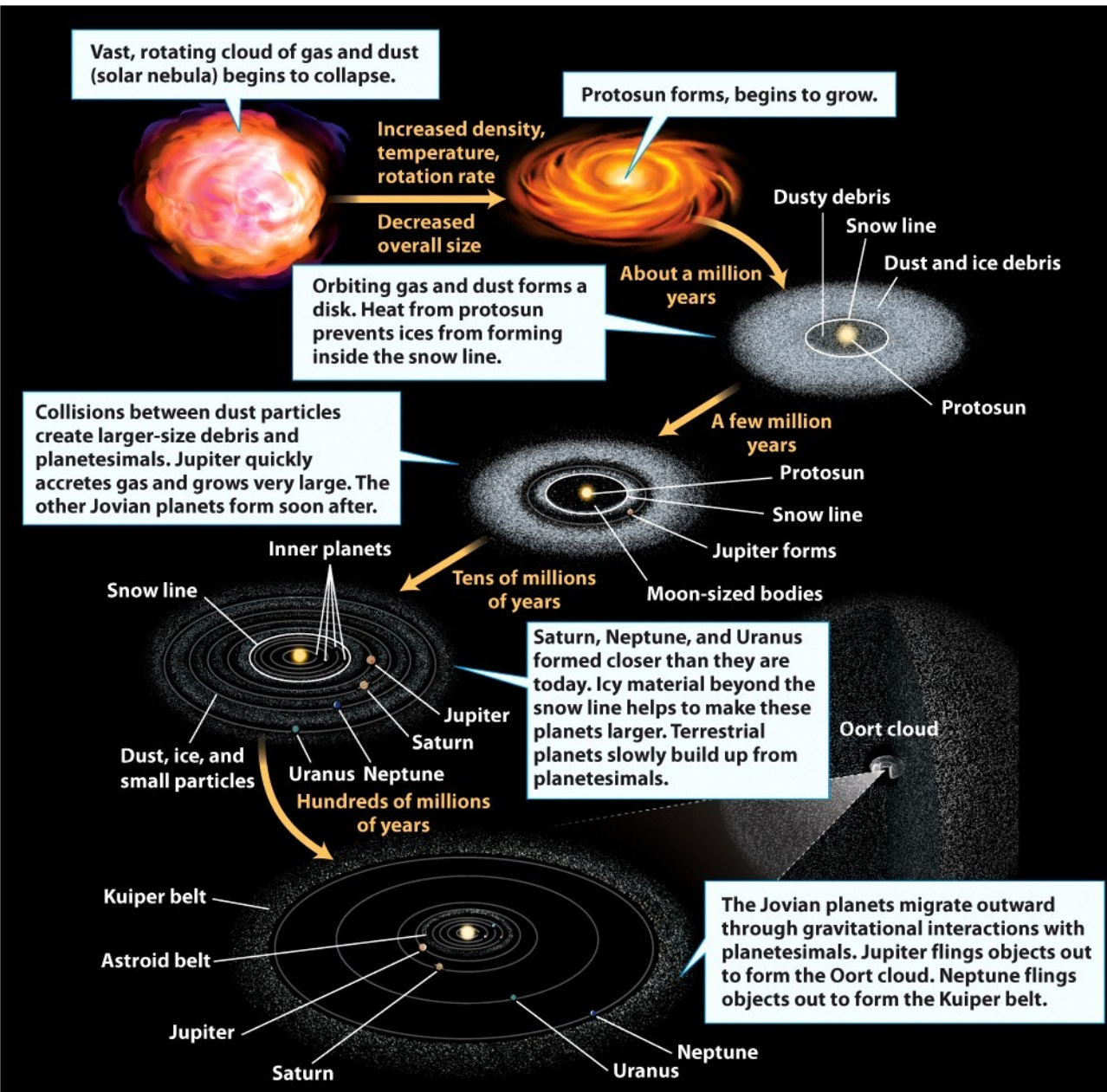


Figure 8-13
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Formation of the Outer Solar System

Further out from the Sun, Saturn would have formed in a similar way. Jupiter and Saturn would have had a disk surrounding them. These would have formed the numerous moons. Uranus and Neptune would have formed further out where there were even more frozen gases, e.g. methane.

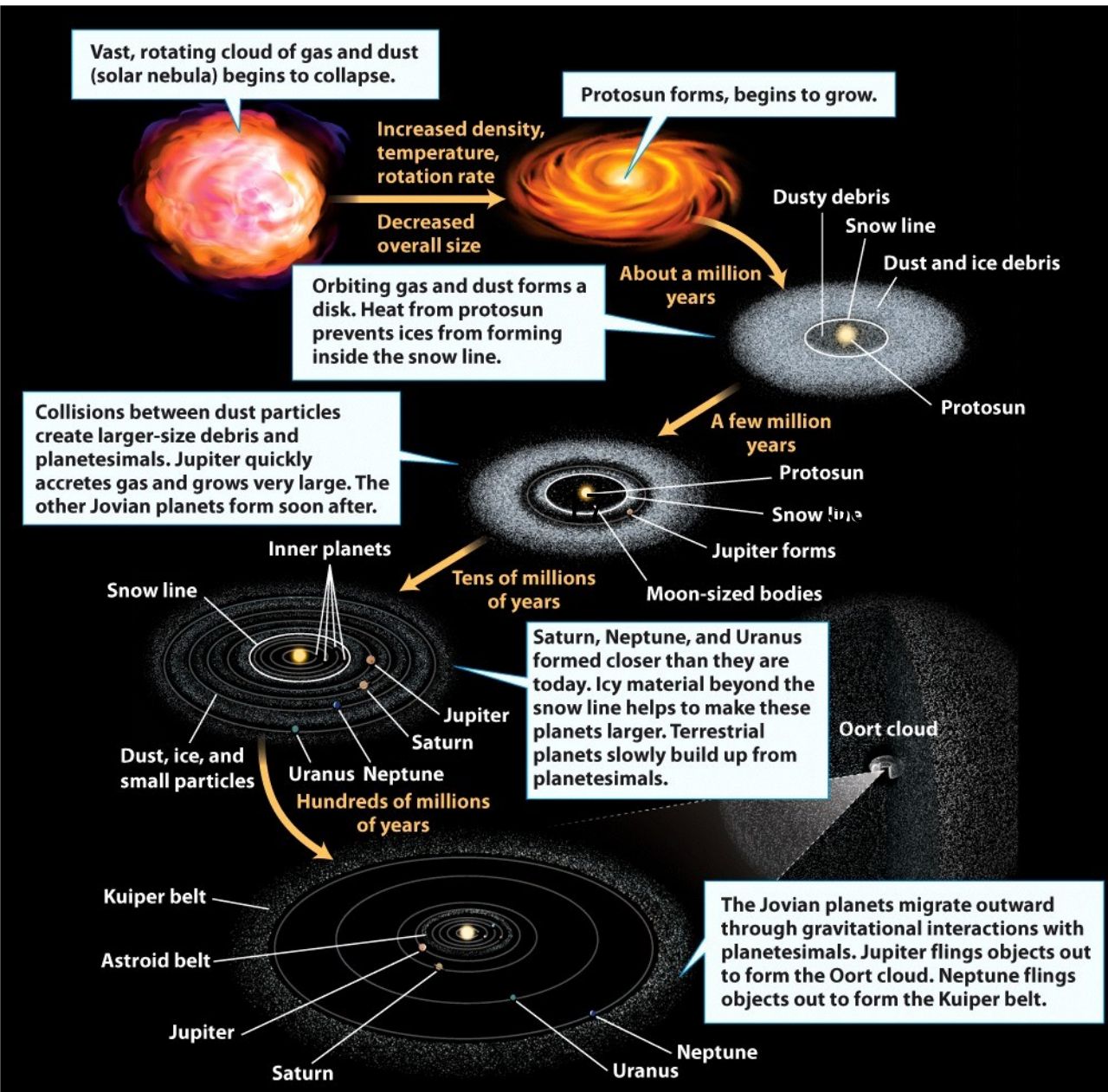


Figure 8-13
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Inward Migration of the Jupiter

As Jupiter grew large by accreting H and He and even before the terrestrial planets formed, gravity pulled it closer to the sun. Computer models suggest Jupiter's orbit moved as close as 1.5 AU from the Sun. This is about the current orbital location of Mars. This deflected many of the planetesimals from this orbital region. This may also account for the relatively smaller mass of Mars.

At the same time, Jupiter may have pulled colder material with frozen ices inward which could account for the rock and ice composition of the asteroid belt.

Outward Migration of the Jovian Planets

The 'Nice' computer model suggests the Jovian planets all formed about 20 AU from the Sun. As the early Jovian planets encountered smaller planetesimals from outside of their orbit, they received a small outward gravitational 'kick' as they deflected the planetesimals inward. Jupiter's being so massive was moved outward less than the smaller Jovian planets. Many of the planetesimals that encountered Jupiter were dispersed to remote regions of the solar system (50,000 AU) which form the Oort cloud.

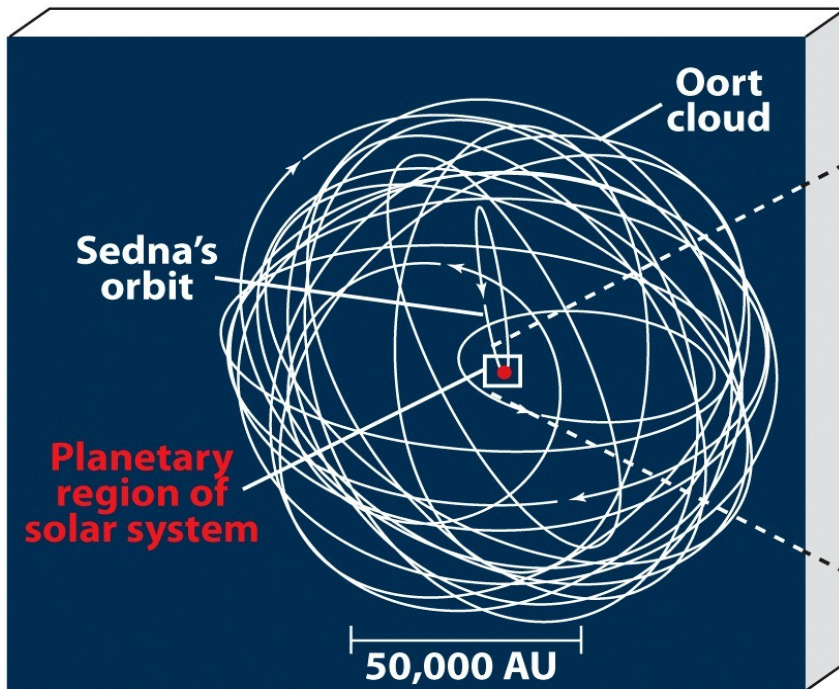


Figure 8-14a part 2
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Outward Migration of the Jovian Planets

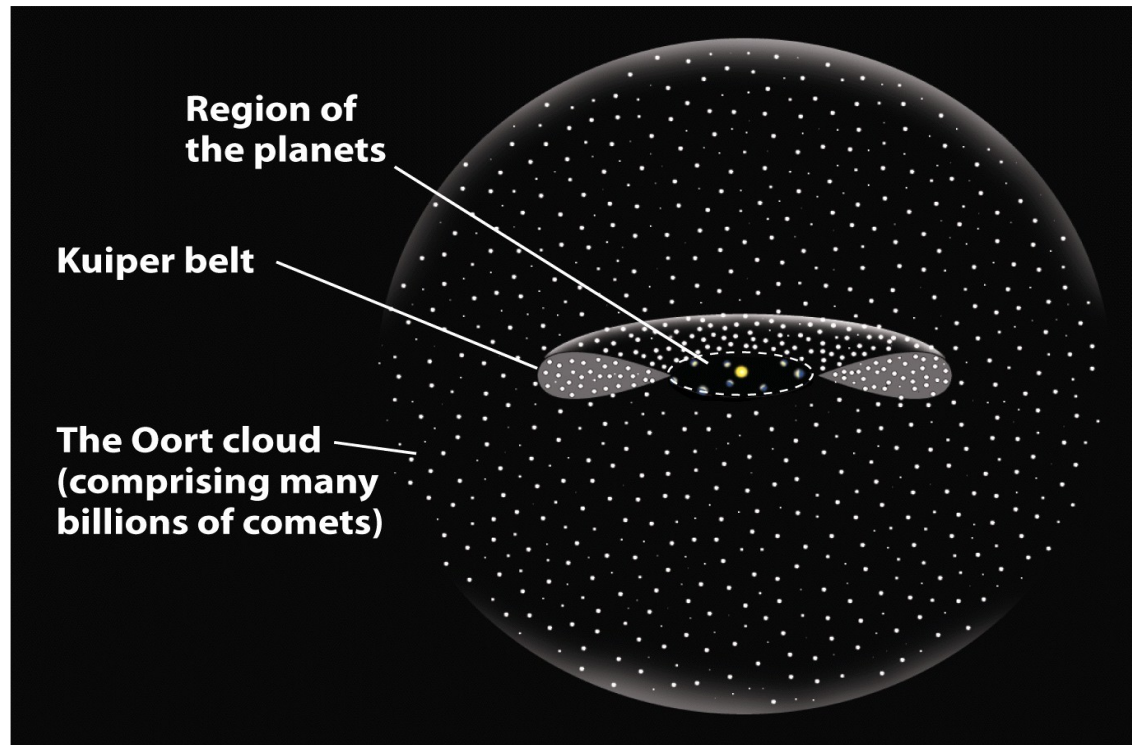


Figure 8-14a part 1
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The outward movement of Neptune to its current location 30 AU from the Sun ejected planetesimals into the Kuiper belt. As the Jovian planets' orbits changed and moved outward to their present positions, they also deflected planetesimals toward the inner solar system, which led to a late heavy bombardment of the terrestrial planets.

Exoplanets

Exoplanets are planets that orbit stars other than our Sun. Before the 1990s, exoplanets were thought to exist but none had been detected or observed. Because stars are so far away they are very difficult to detect. Only recently that exoplanets have been observed. There are two main methods of detecting exoplanets.

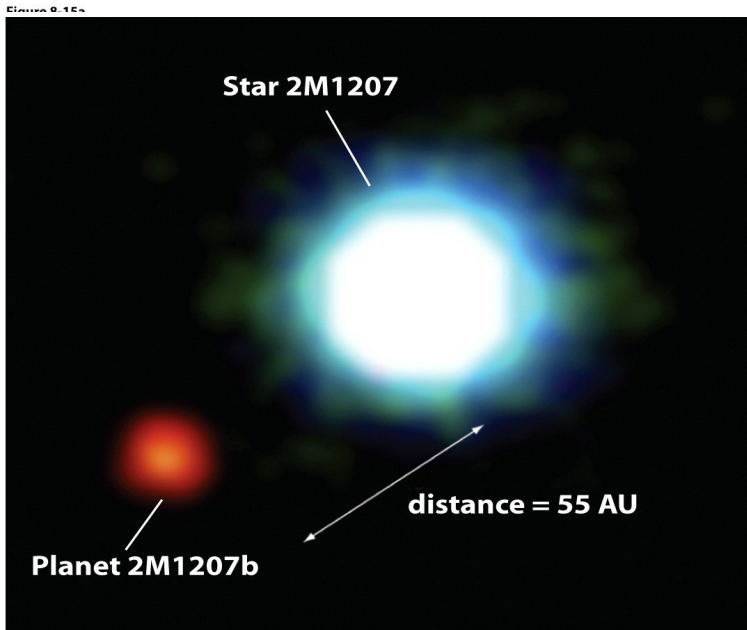
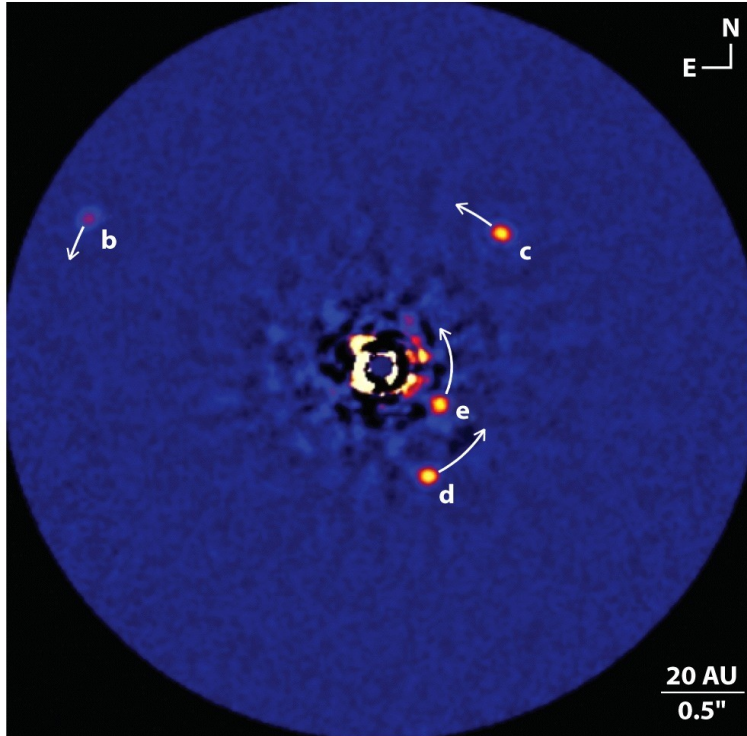
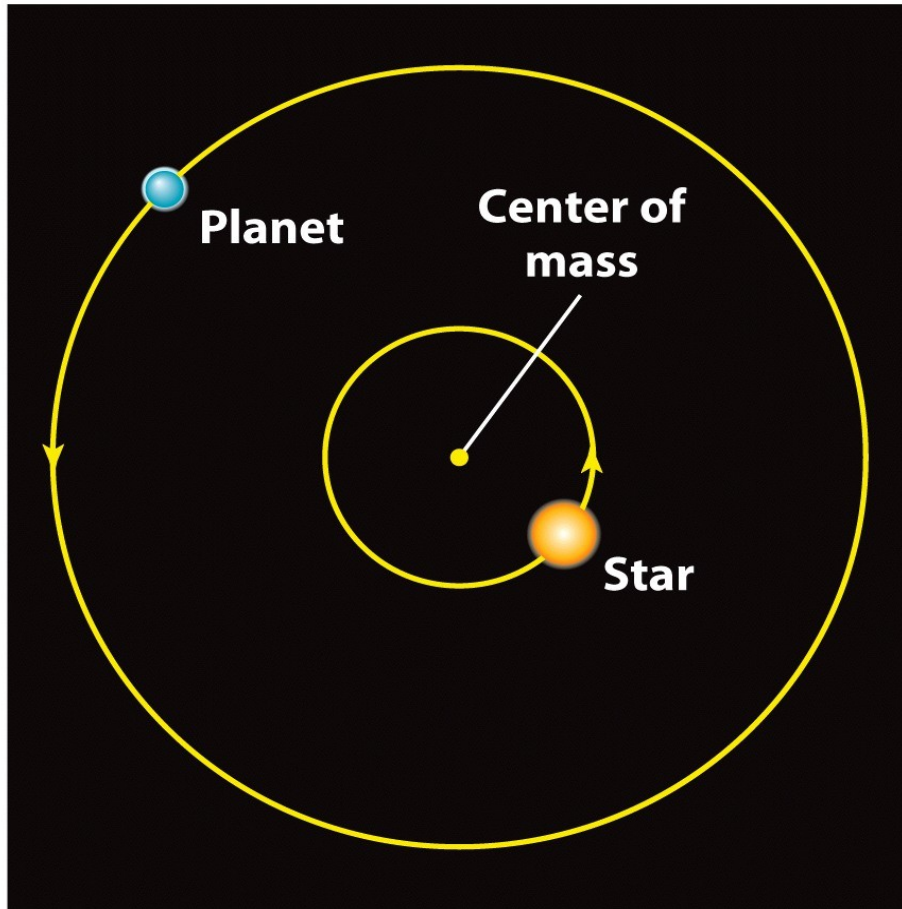


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ESO/VLT/NACO

The Wobbling Stars



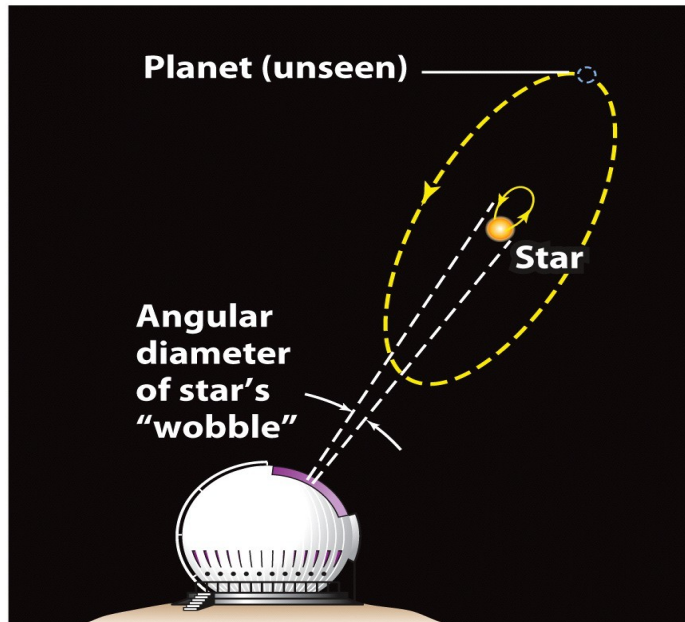
A star and its planet

Figure 8-16a
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The 'astronomical method' and 'radial velocity method' uses the fact that when a large planet orbits a star, the star moves around the center of mass of the star planet system just as the planet does. This causes the star to 'wobble' back and forth. It only works when the plane of the orbiting planet is edge on to the viewpoint from the Earth.

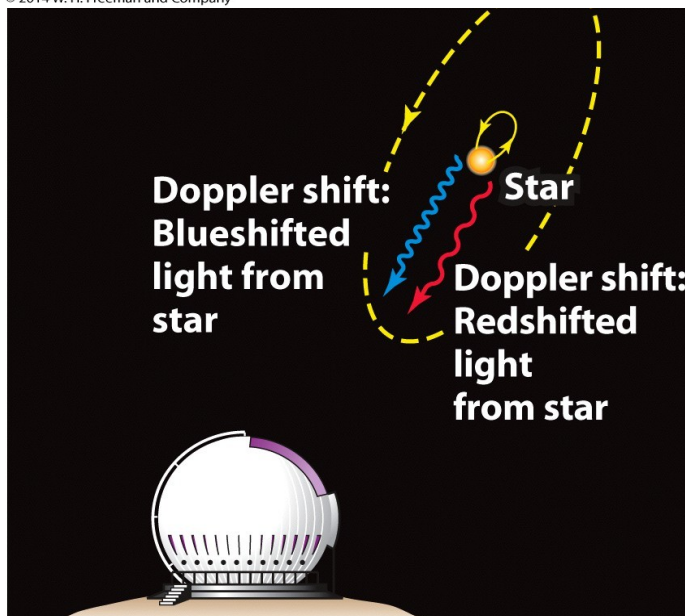
The Wobbling Stars

In the 'astronomical method', the angular diameter of the star's wobble is measured. It normally takes a large planet near a nearby star to measure a small angular wobble in the star. It requires very accurate measurements (0.001 arc seconds or better).



The astrometric method

Figure 8-16b
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In the 'radial velocity' method the Doppler shift of the spectrum of the star is observed to shift back and forth from slightly red shifted to blue shifted and back.

The radial velocity method

The Wobbling Stars

The radial velocity measurement of 51 Pegasi show both the period (and from Kepler's law the semimajor axis) and an estimate of the magnitude of the planets mass. This was the first exoplanet to be discovered around a star. The planet is $\frac{1}{2}$ the mass of Jupiter and orbits at 0.05 AU in 4.23 days!

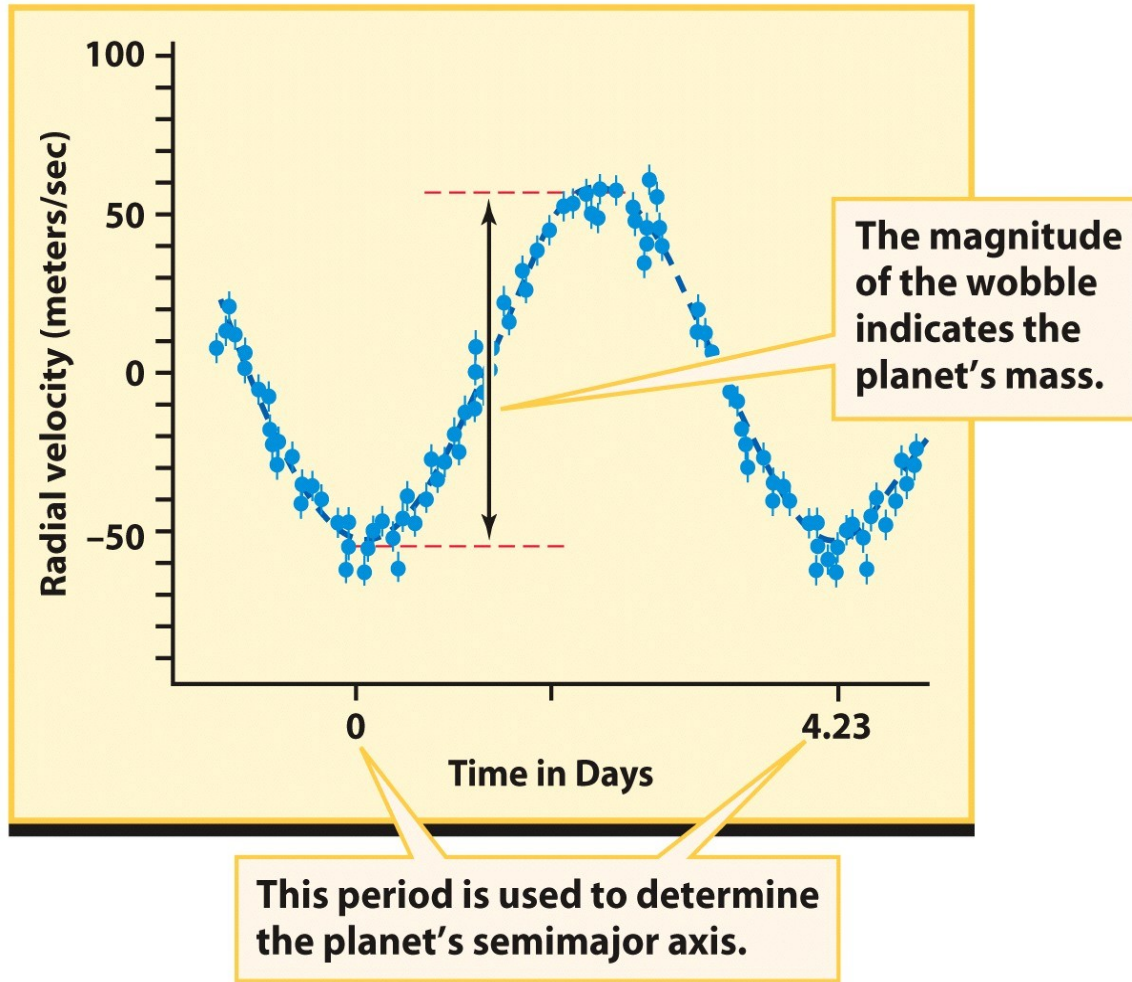


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The Transit Method

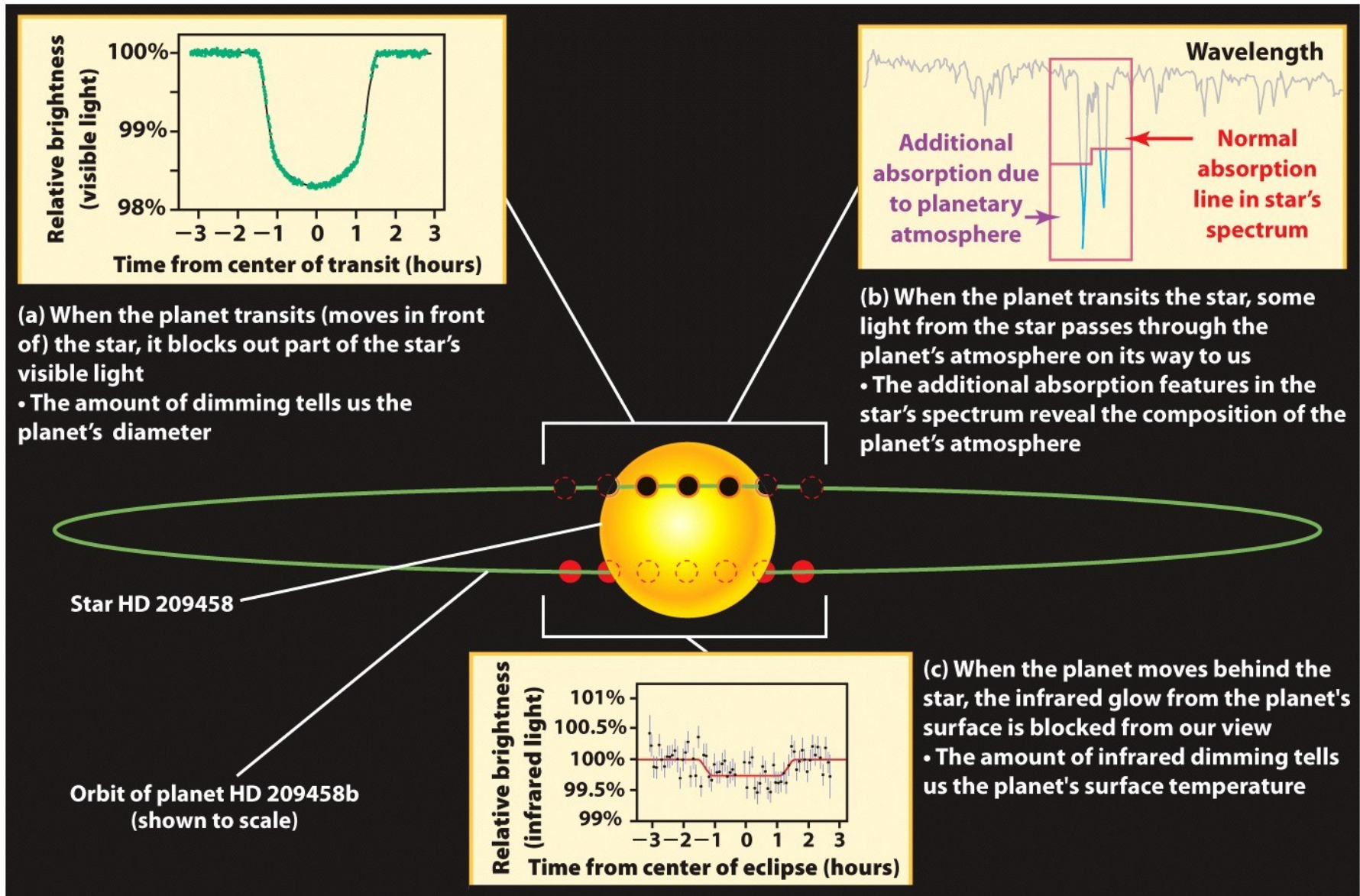


Figure 8-19

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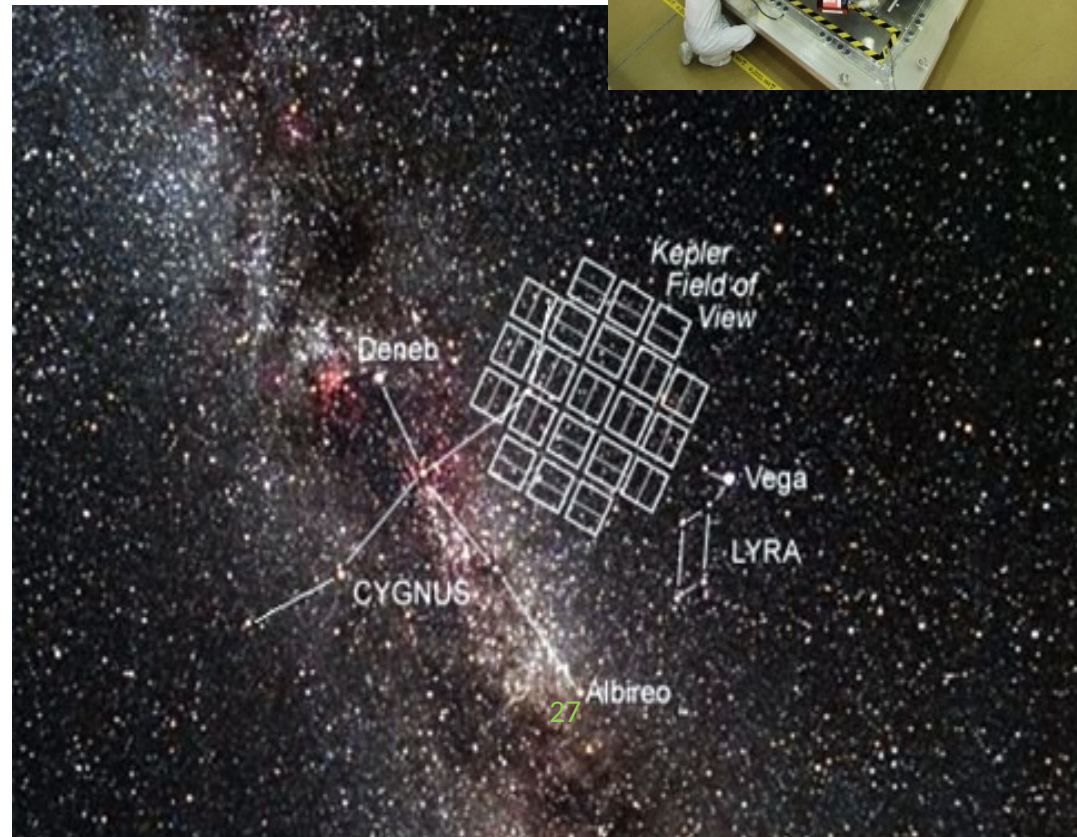
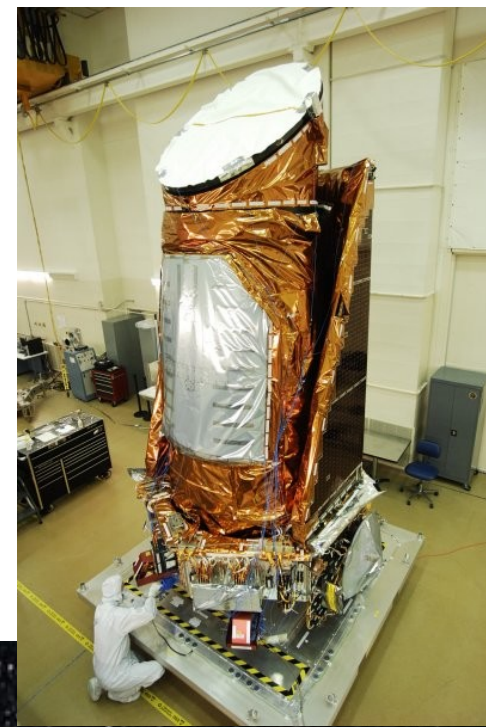
S. Seager and C. Reed, Sky and Telescope; H. Knutson, D. Charbonneau, R. W. Noyes (Harvard-Smithsonian CfA), T. M. Brown (HAO/NCAR), and R. L. Gilliland (STScI); A. Feild (STScI); NASA/JPL-Caltech/D. Charbonneau, Harvard-Smithsonian CfA

The Transit Method

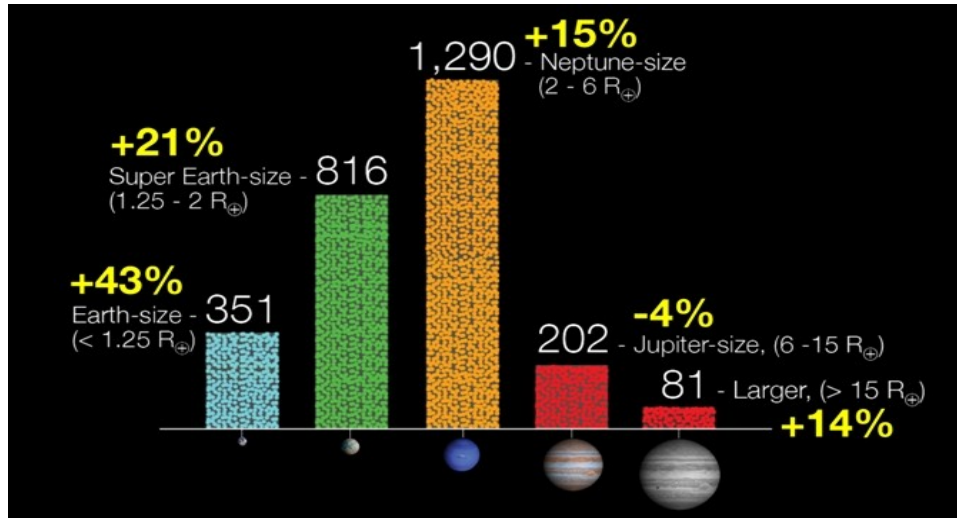
The transit method requires the planet's orbit to be edge-on (only about 0.4% of planets). With the transit method, we can get more information about the planet than from the other methods.

- The amount by which the star is dimmed during the transit depends on the size of the planet.
- If the planet has an atmosphere, the light passing through the atmosphere gives an absorption spectrum indicating the composition.
- Since the planet emits infrared radiation of its own, when the planet is behind the star the total infrared radiation is decreased. This can be used to determine the temperature of the planet.

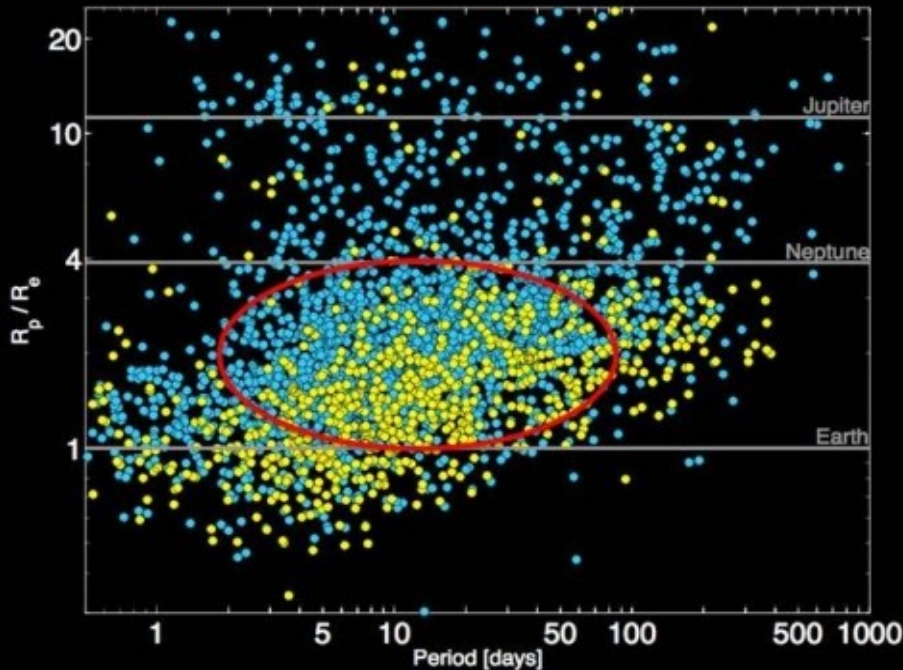
- Kepler space telescope in orbit around the Sun
- Kepler has released data over two years of observations (has collected over 4 years)
- Looks at a patch of sky near edge of the Milky Way
- Uses the transit method
- Responsible for the majority of discovered planets
 - > But large false positive rate
- Only sensitive to orbits less than about 1.5 years and most sensitive to larger planets
- Recently failed



Data from Kepler

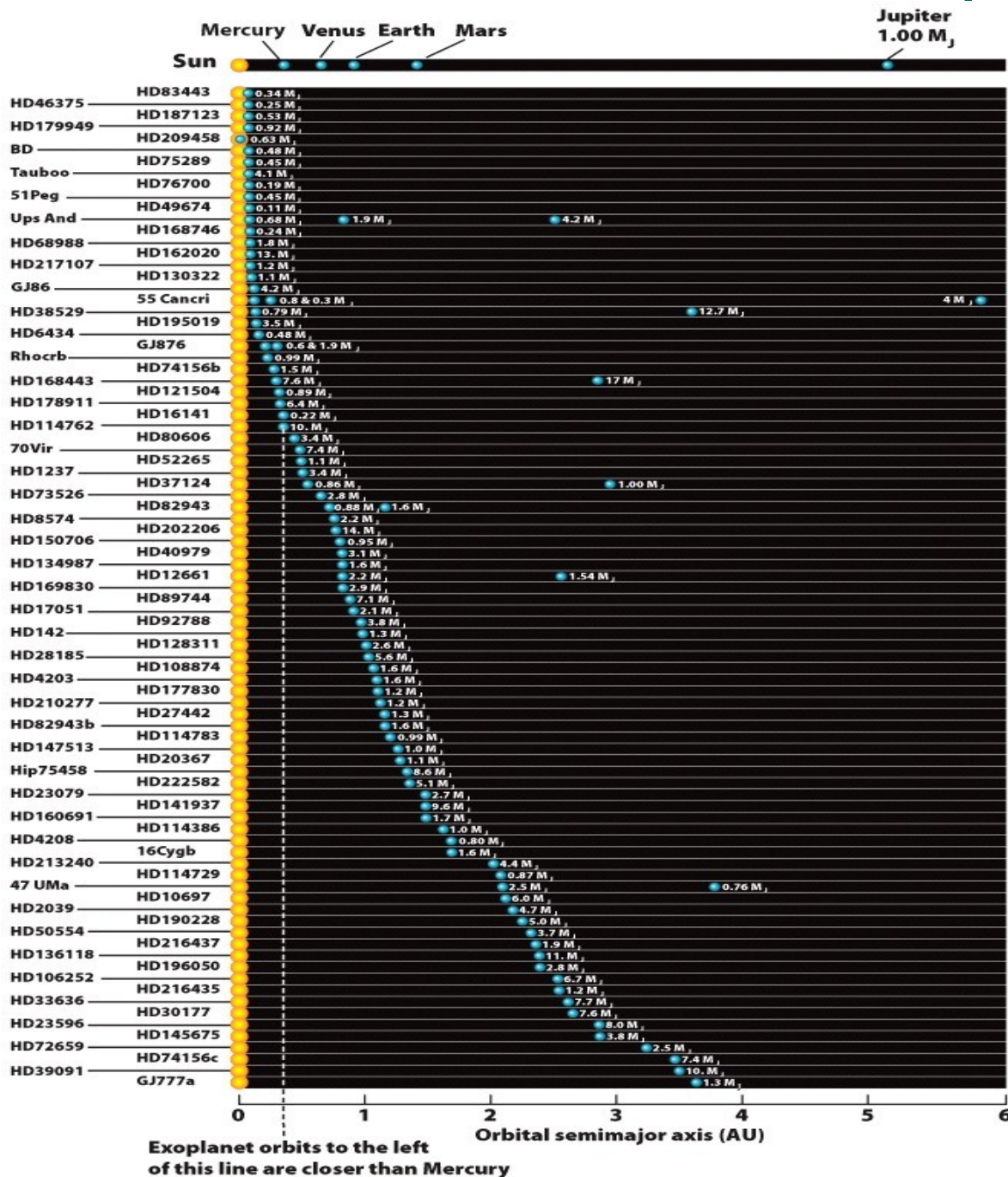


Kepler Planet Candidates
January 2014



Kepler was designed to detect Earth sized planets that were in the habitable zone or 'Goldilocks zone' (not too hot and not too cold) Liquid water could exist on such a planet which opens the possibility of life existing on such an exoplanet.

Known Exoplanets



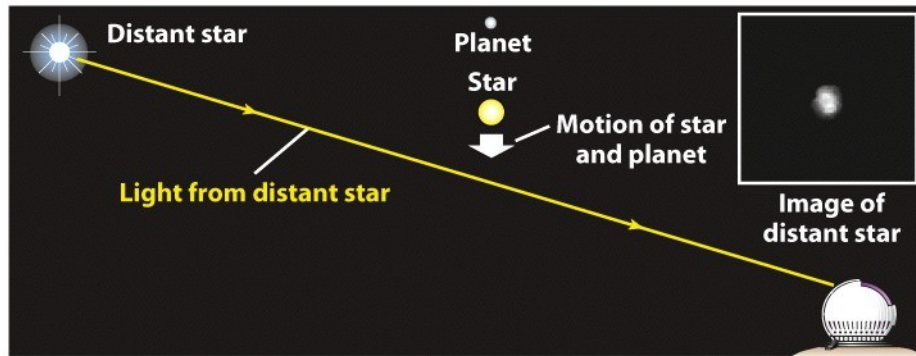
The Kepler data analysis estimates that about 5.4% of stars in the Milky Way have Earth like planets and that 17% of stars have multiple planet system. Over 2000 exoplanets have been discovered.

Figure 8-18

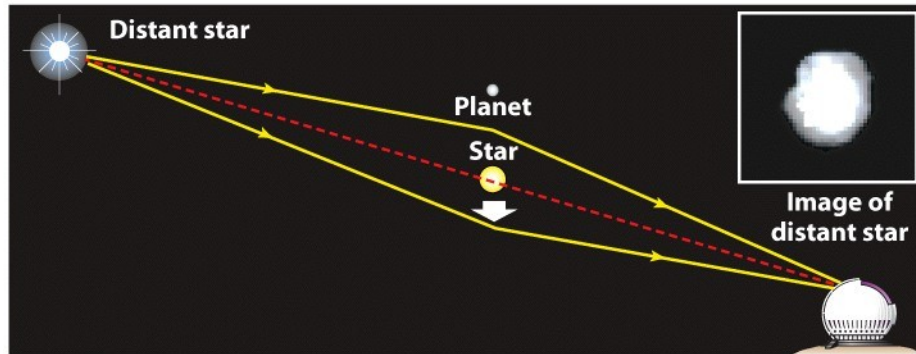
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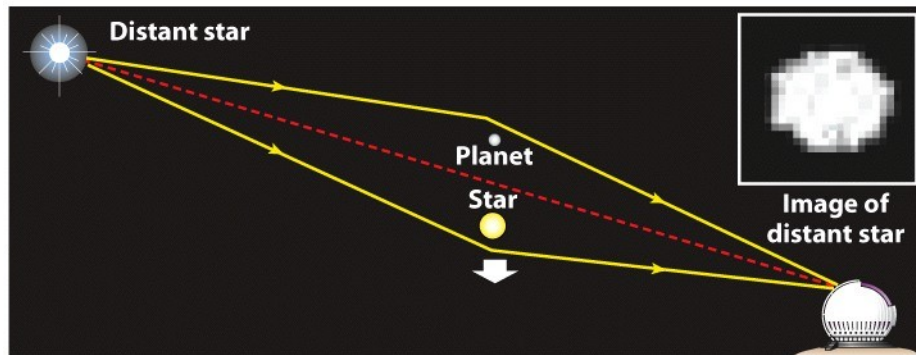
Microlensing



(a) No microlensing



(b) Microlensing by star



(c) Microlensing by star and planet

Gaia is ESA satellite mission to chart a three-dimensional map of our Galaxy, the Milky Way, in the process revealing the composition, formation and evolution of our Galaxy. The Gaia data can be used to search for exoplanets using gravitational 'microlensing'. Gaia went into orbit one year ago and expect to observe 1 billion stars