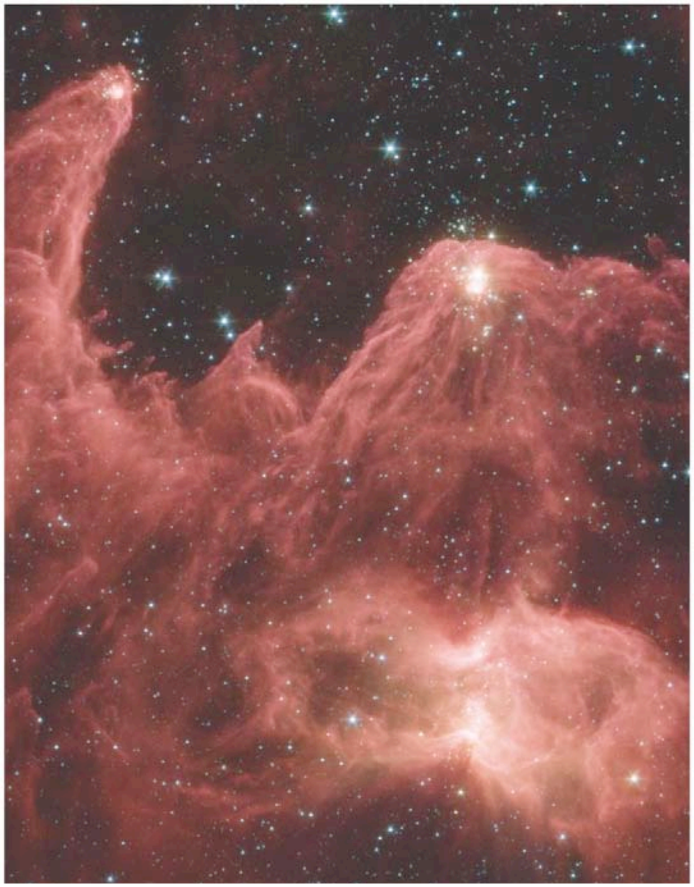
Chapter 15

The Formation of Planetary Systems



Units of Chapter 15

15.1 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**
5. **Direction of most planets' rotation is also the same as the Sun's**

15.1 Modeling Planet Formation (cont.)

6. **Most moons' orbits are also in the same sense**
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**

15.1 Modeling Planet Formation

Solar system is evidently not a random assemblage, but has a single origin.

Planetary condensation theory, first discussed in Chapter 6, seems to work well.

Lots of room for variation; there are also irregularities (Uranus's axial tilt, Venus's retrograde rotation, etc.) that must be allowed by the model.

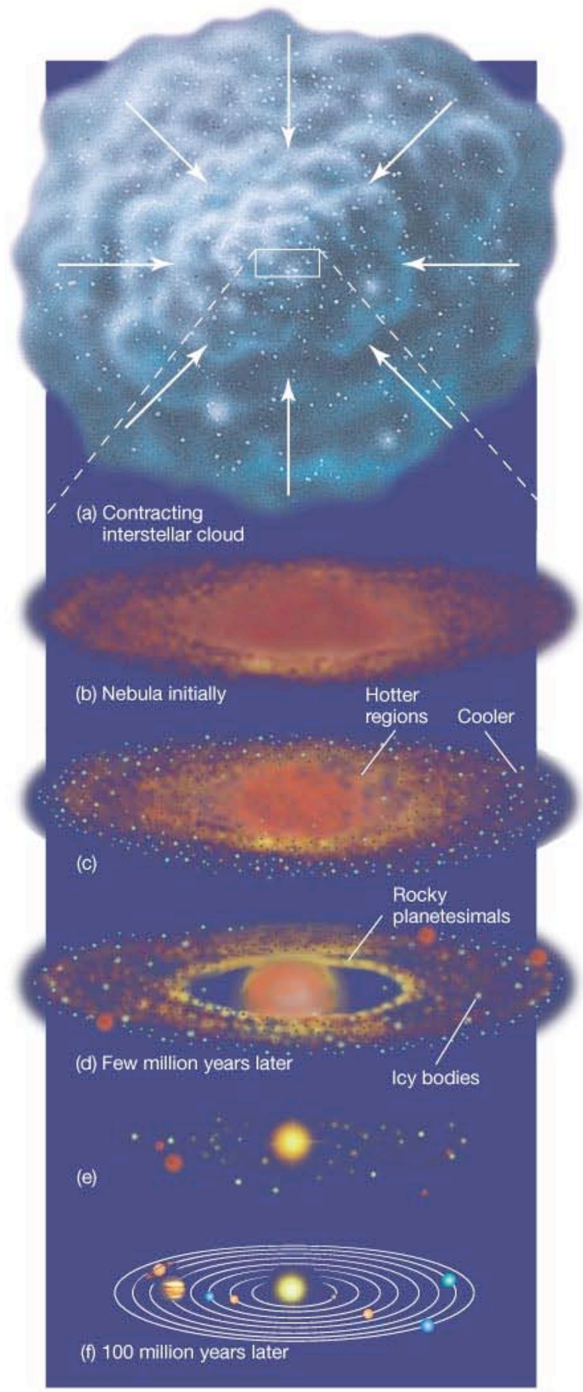
Review of condensation theory:

- Large interstellar cloud of gas and dust starts to contract, heating as it does so.

- Sun forms in center; residual material forms a disk because of the influence of *rotation*, may fall into the growing Sun, or condense into planets.

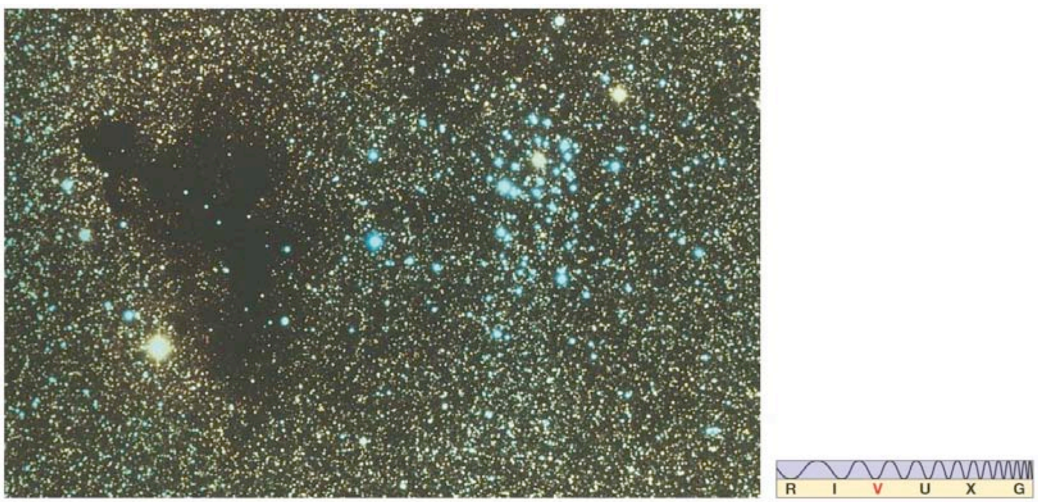
- The dust in the disk provides condensation nuclei, around which planets form.

- As planets grow, they sweep up ("accrete") smaller debris near them

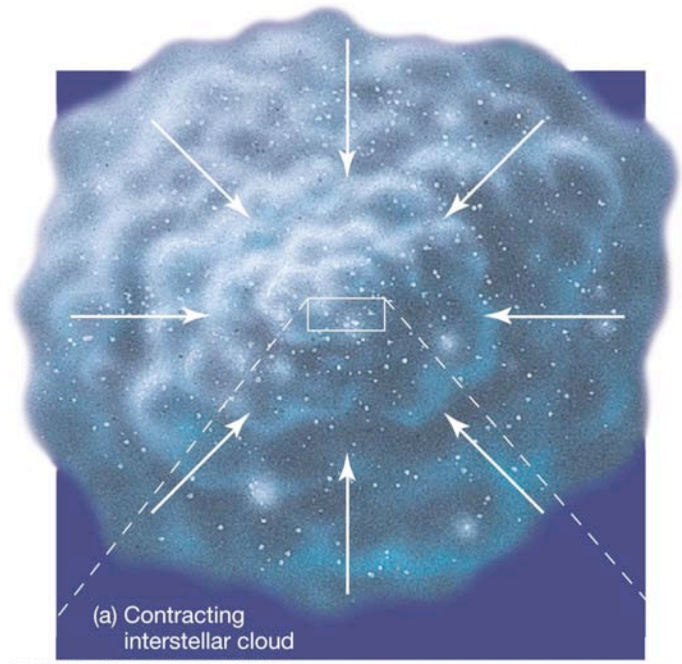


First stage: the Sun forms from an interstellar cloud of gas and dust

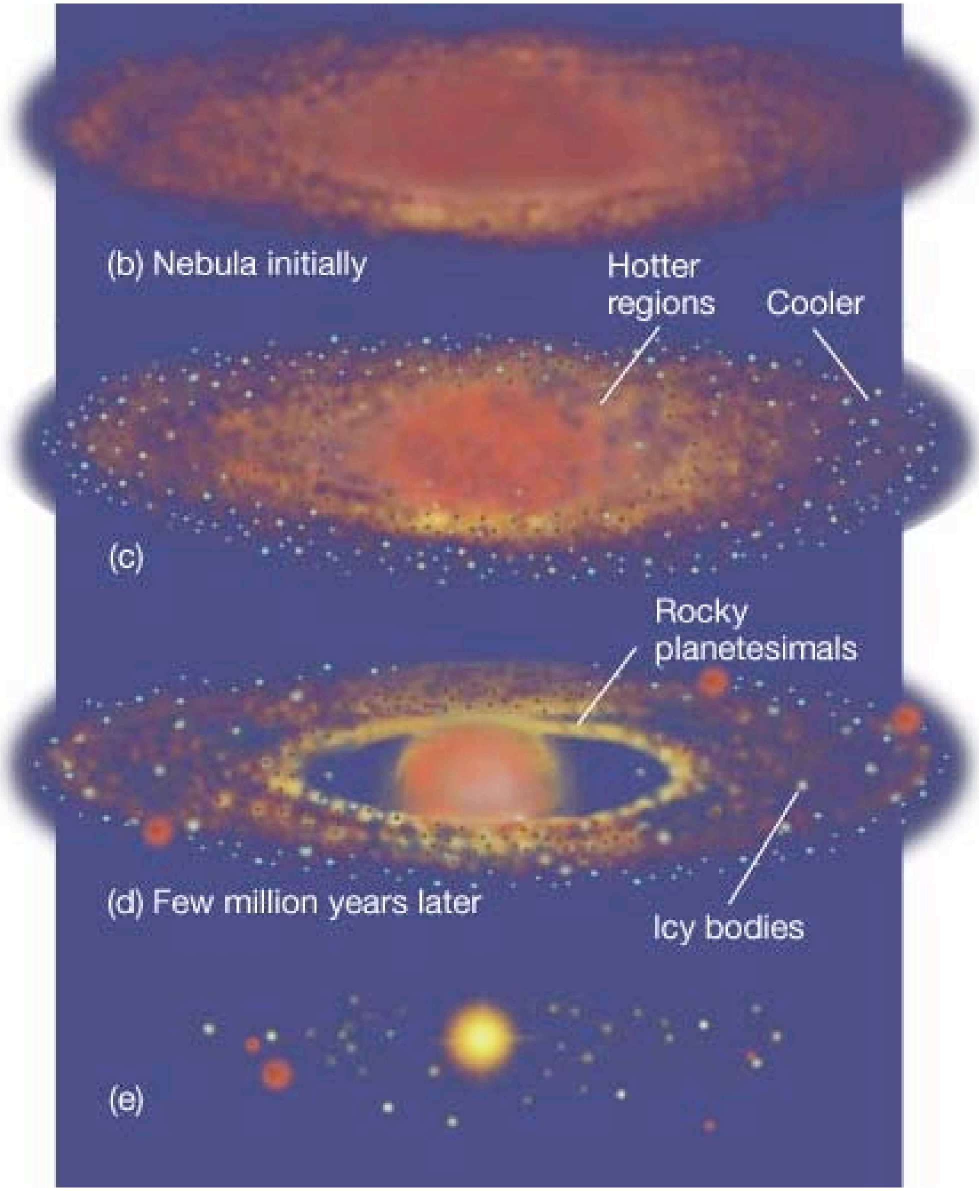
This “dark” dust cloud is believed to be a site of star formation:



Subregions within a large cloud collapse under their own gravity, Forming clusters of stars



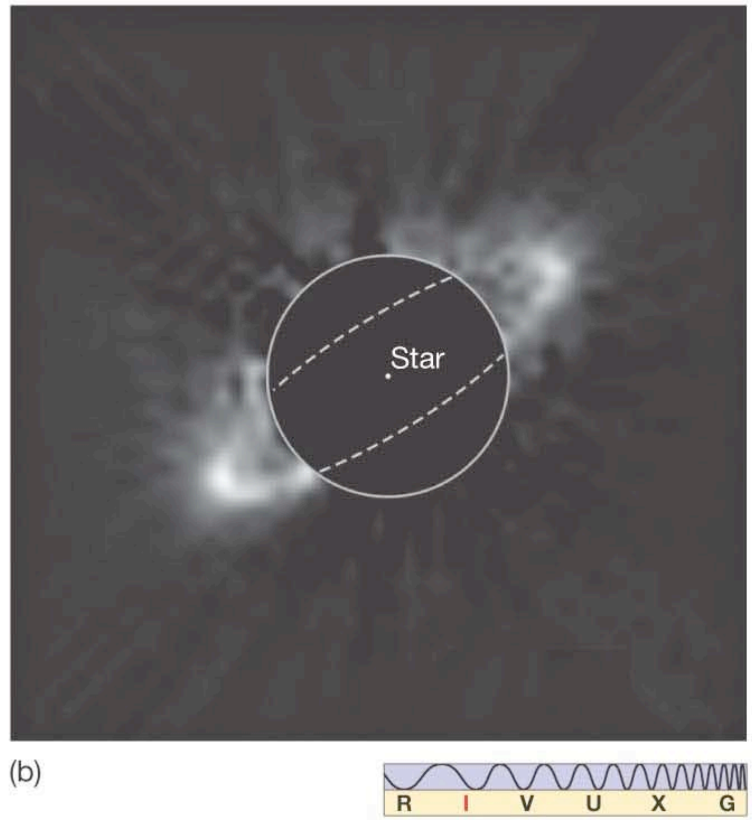
The difficult part is the formation of planets from a disk of dust grains and gas:



Is there observational evidence for disks around young stars?

These accretion disks surrounding stars in the process of forming are believed to represent the early stages of planetary formation. An important observation is that nearly *all very young stars are surrounded by dusty disks.*

(a)



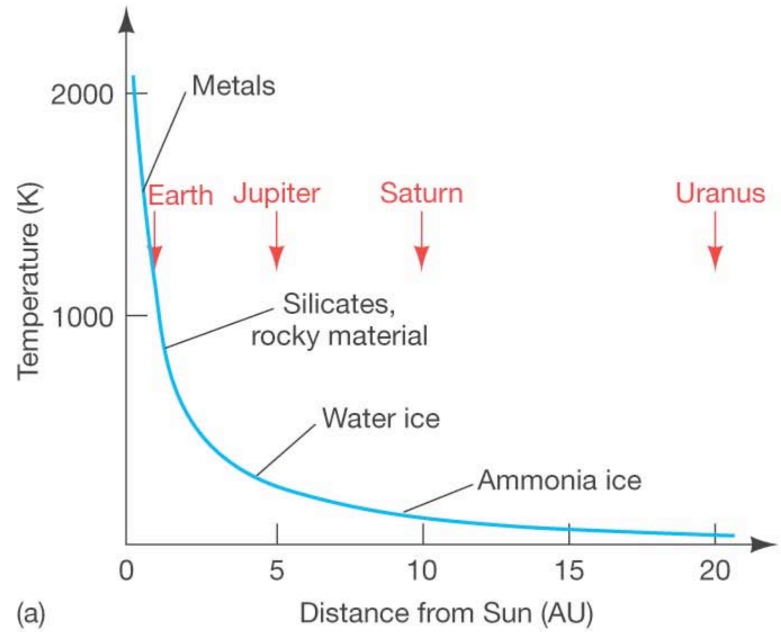
(b)

15.2 Formation of the Solar System

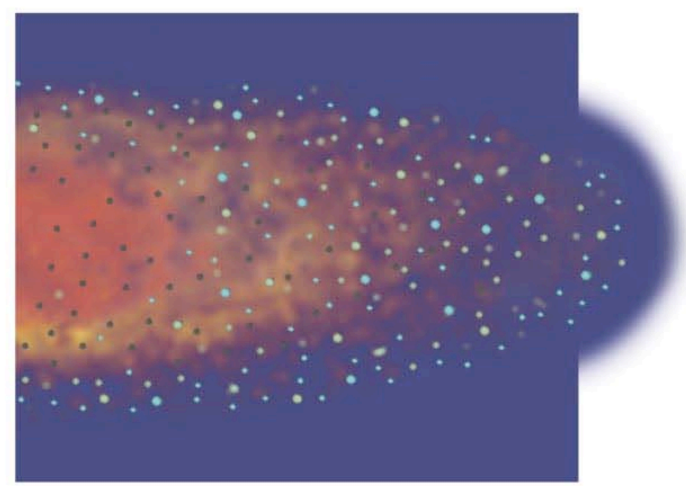
The following fact explains many of the properties of the planets, especially the difference between terrestrial and gas giants:

The farther away one gets from the newborn Sun, the lower the temperature. This caused different materials to predominate in different regions—rocky planets close to the Sun, then the gas giants farther away.

Study illustrations to the right.



(a)



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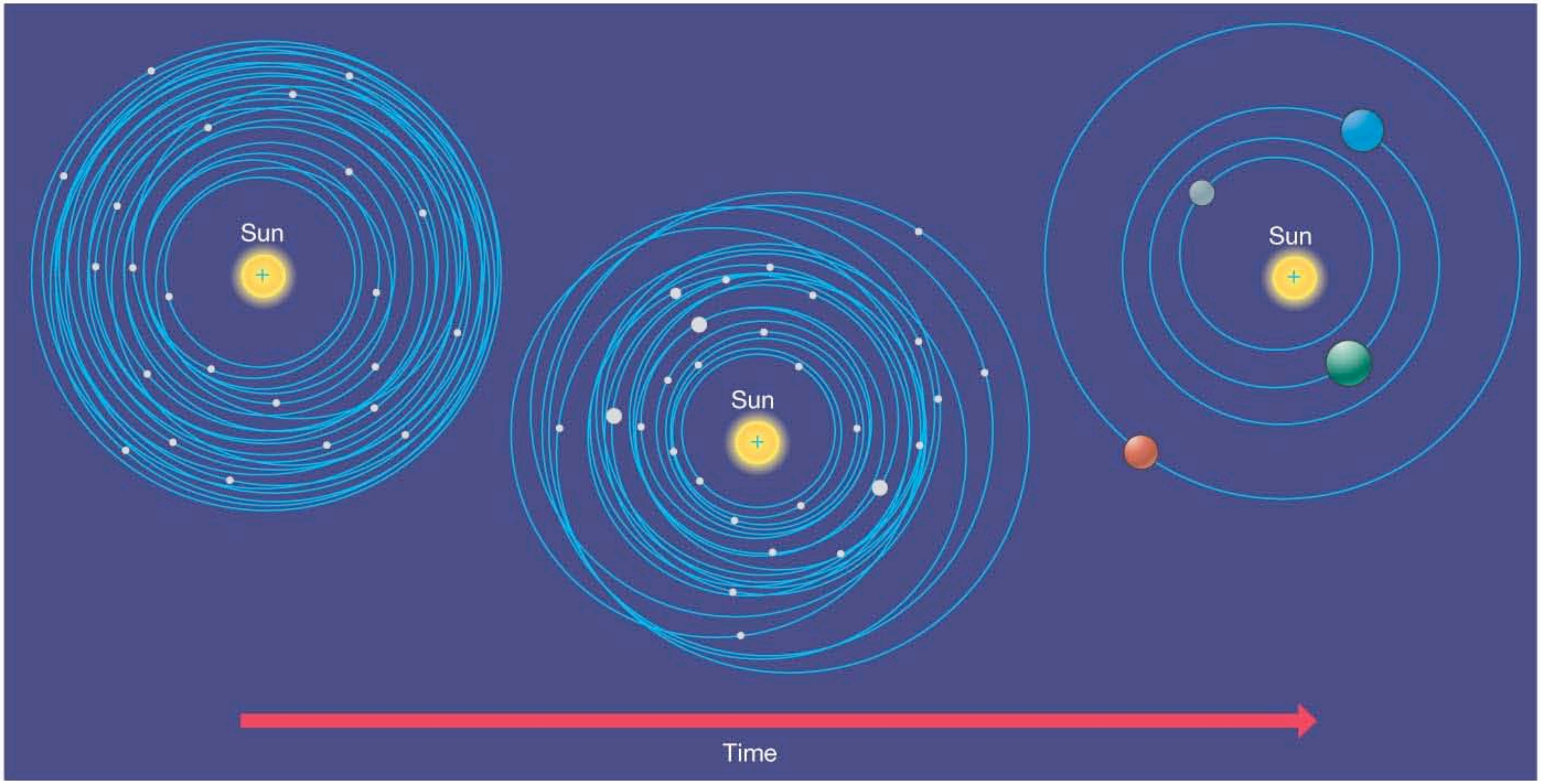
15.3 Terrestrial and Jovian Planets

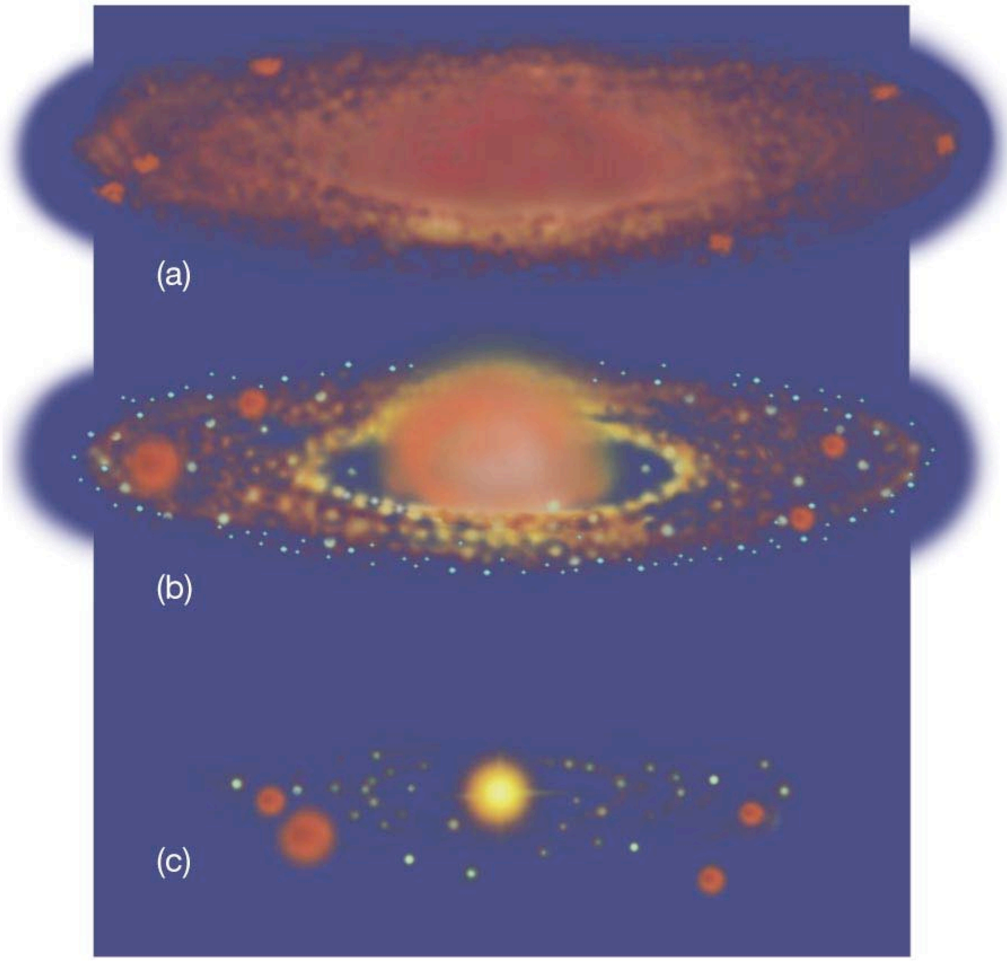
Terrestrial (rocky) planets formed near Sun, due to high temperature—nothing else could condense there. Ices all vaporize at temperatures above about 100K.



Jovian planets:

- Once they were large enough, may have captured *gas* from the contracting nebula

- Or may have formed from instabilities in the outer, cool regions of the nebula. The main instability involves the gravity of a large clump causing it to collapse.



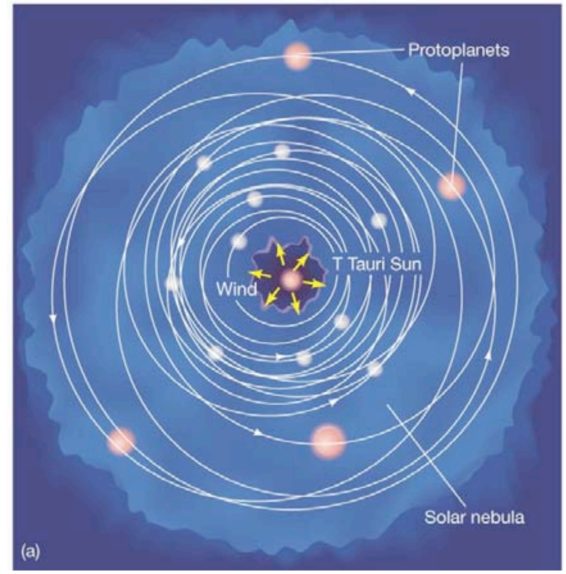
Detailed information about the cores of jovian planets should help us distinguish between the two possibilities.

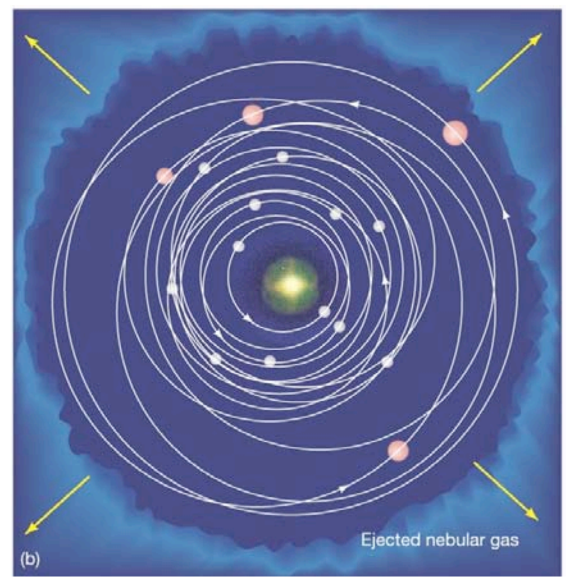
Also possible: The jovian planets may have formed farther from the Sun and "migrated" inward.

15.3 Terrestrial and Jovian Planets

A problem for forming giant planets: You have to form them quickly, because the gas in disks is observed to disappear in a relatively short time, about 5 million years. Where does it go? The central star probably blows it away.

T Tauri stars are in a highly active phase of their evolution and have strong solar winds. These winds sweep away the gas disk, leaving the planetesimals and gas giants.





15.4 Interplanetary Debris

Asteroid belt:

- Orbits mostly between Mars and Jupiter
- Jupiter's gravity kept them from condensing into a planet, or accreting onto an existing one
- Fragments left over from the initial formation of the solar system

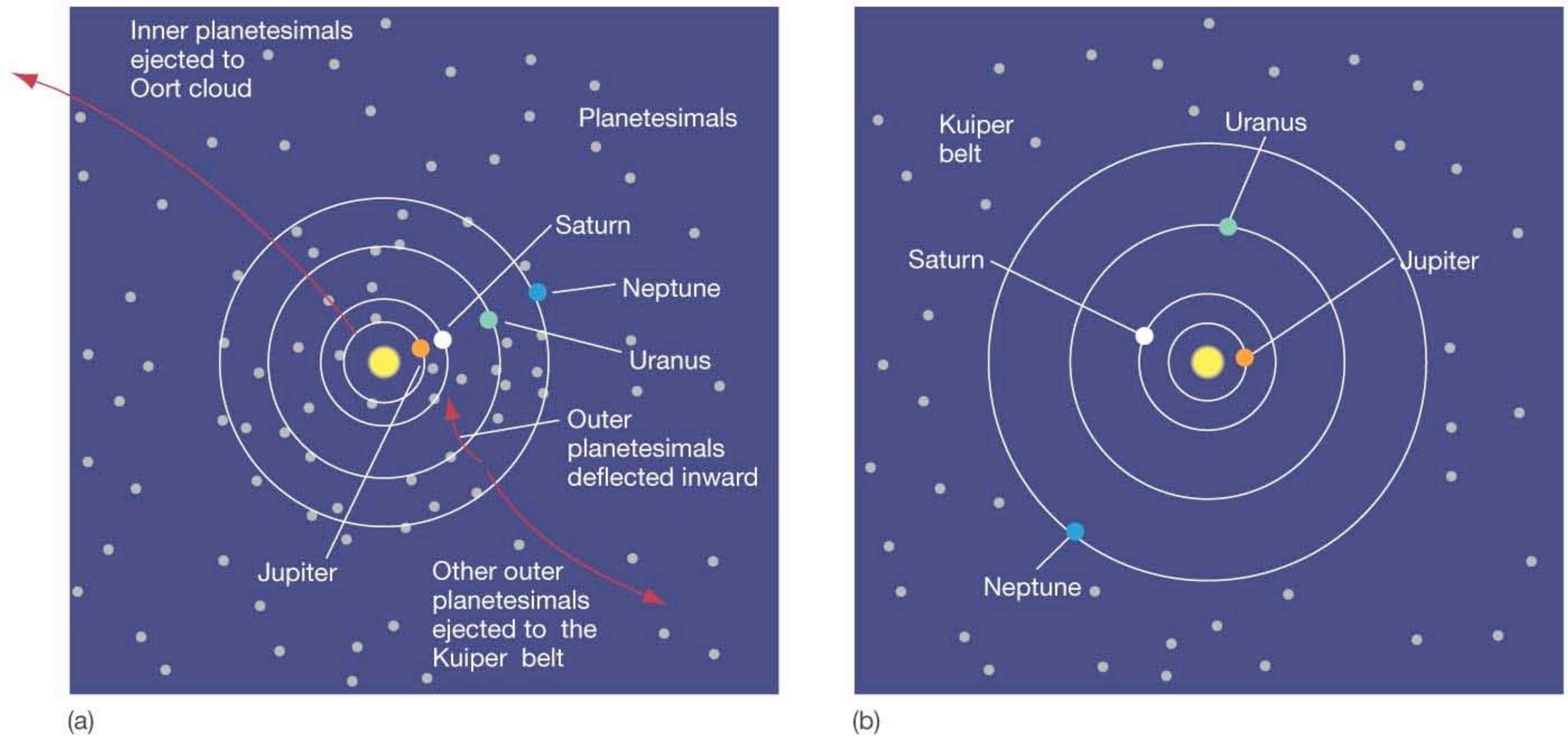
15.4 Interplanetary Debris

Icy planetesimals far from the Sun were ejected into distant orbits by gravitational interaction with the jovian planets, into the Kuiper belt and the Oort cloud.

Kuiper-belt objects have been detected from Earth recently; a few are as large as, or larger than, Pluto, and their composition appears similar.

About 1/3 of all Kuiper belt objects (including Pluto) have orbits that are in a 3:2 resonance with Neptune; such objects are called "plutinos."

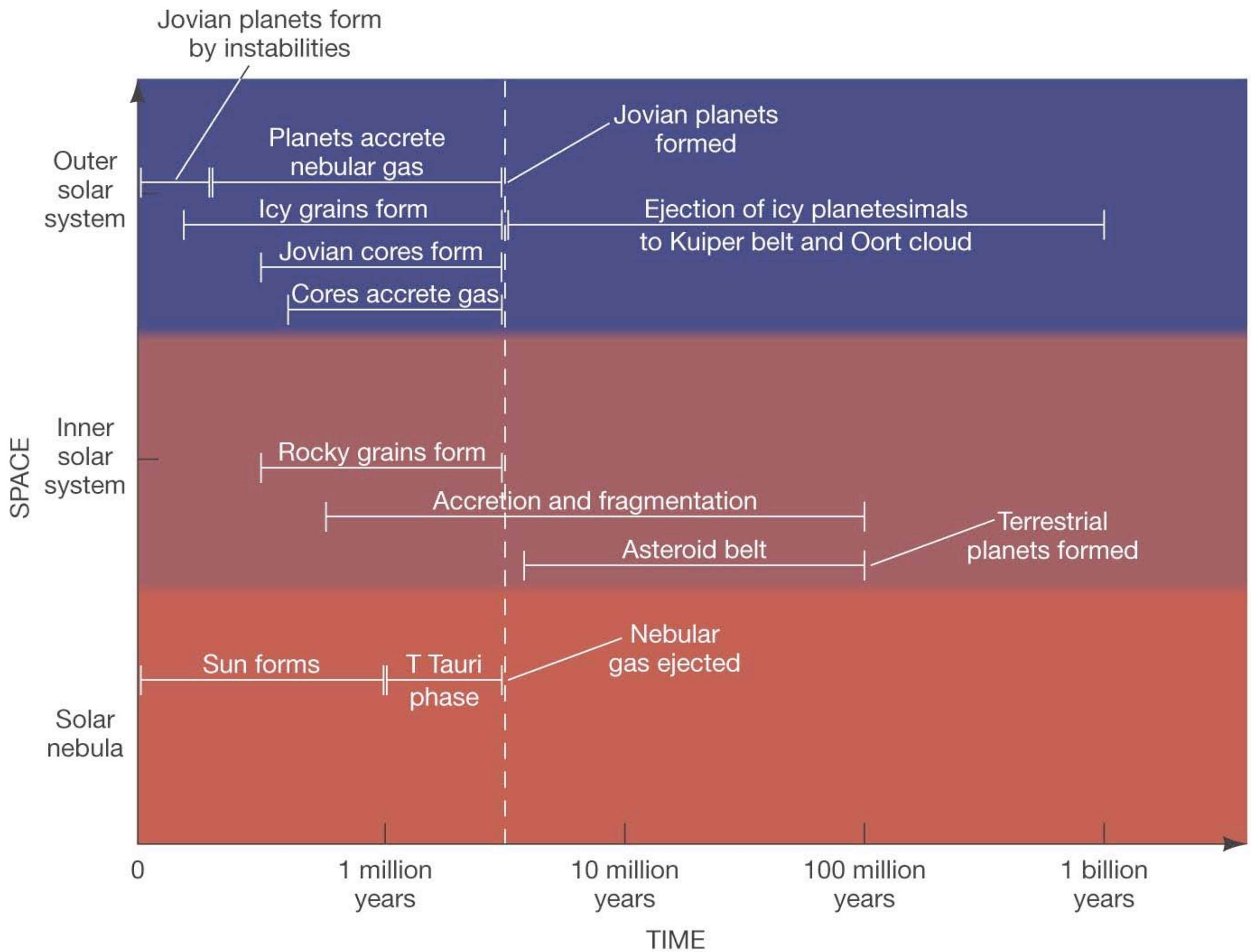
Some were left with *extremely eccentric orbits* and appear in the inner solar system as comets.



15.4 Interplanetary Debris

General timeline of solar system formation: (too much detail--and most of it is very uncertain! Just take this to mean “We wish we could make an accurate timeline like this.”

Translation: not on exam.



15.5 Solar System Regularities and Irregularities

Condensation theory (collisions of rocks followed by accretion for giant planets) covers the 10 points mentioned at the beginning.

What about the exceptions?

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 (to explain strange rotation)

3. Earth–Moon system probably formed after a collision.

15.5 Solar System Regularities and Irregularities (cont.)

4. Late collision may have caused Mars's north–south asymmetry and stripped most of its atmosphere.

5. Uranus's tilted axis may be the result of a glancing collision.

6. Miranda may have been almost destroyed in a collision.

7. Interactions between jovian protoplanets and planetesimals could be responsible for irregular moons.

15.5 Solar System Regularities and Irregularities (cont.)

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 exceptionally large.

Discovery 15-1:
The Angular Momentum "Problem"

Note: Think of this as "How did all the sun's angular momentum get into the planets?" But this is NOT on exam.

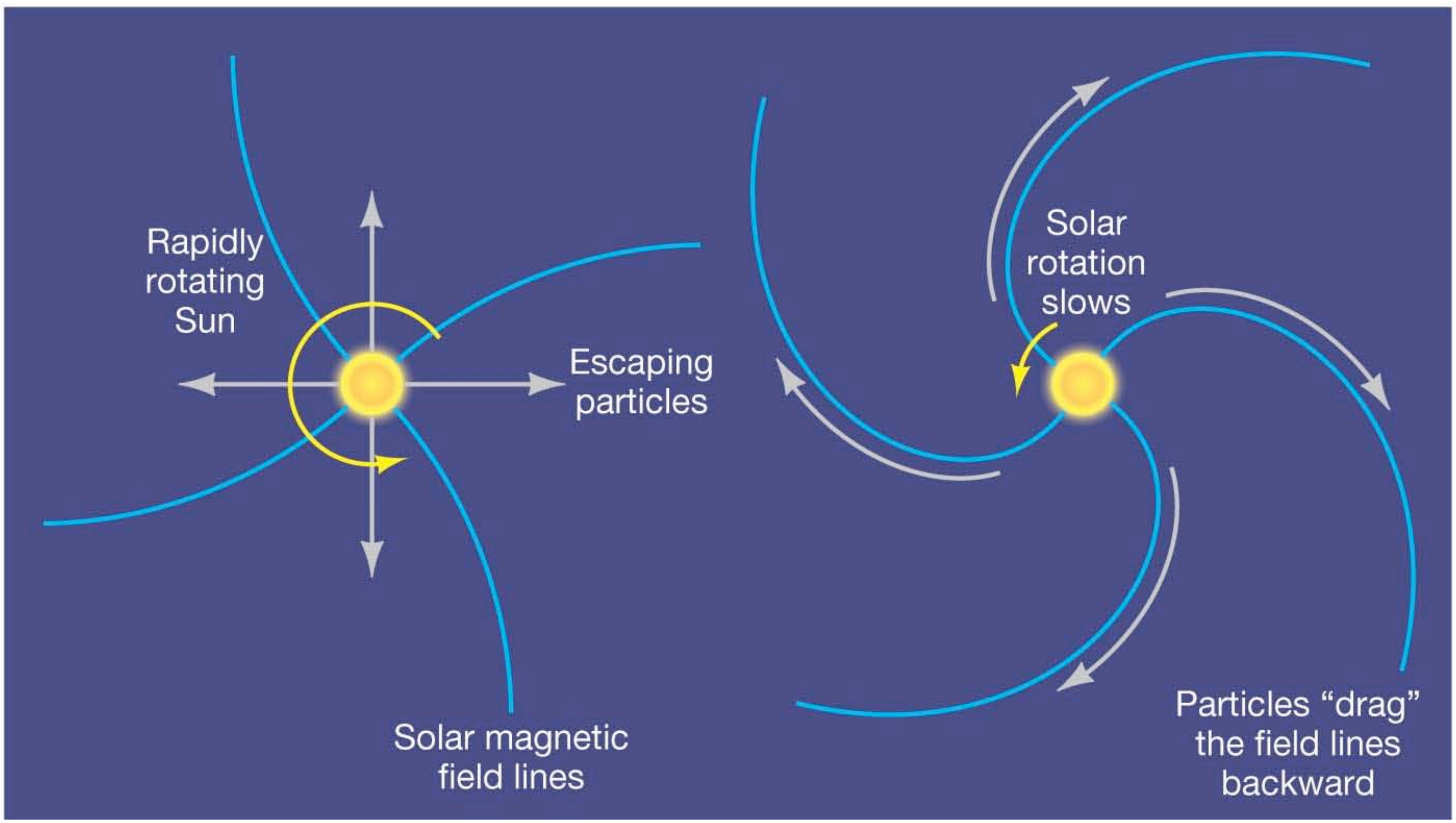
As it collapsed, the nebula had to conserve its angular momentum.

However, at the present day, the Sun has almost none of the solar system's angular momentum:

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

Discovery 15-1:
The Angular Momentum Problem

Theory: The Sun transferred most of its angular momentum to outer planets through friction.



15.6 Planets Beyond the Solar System

Planets orbiting other stars are called "extrasolar planets."

Until 1995, whether or not extrasolar planets existed was unknown.
Since then ***more than 300 have been discovered***.

We want to know:

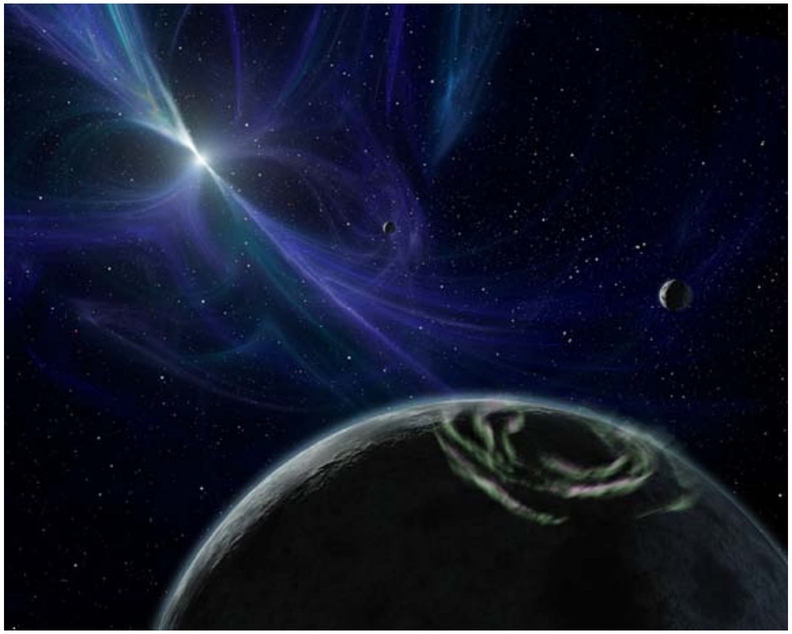
What methods are available for detection of extrasolar planets?

How common are extrasolar planets?

Are they similar to planets in our solar system?

Are other planetary systems like ours, with terrestrial and Jovian (gas giant) planets?

How common are Earth-mass planets? Earth-like planets? Do they have water? Life?
Can you answer these questions by Monday???



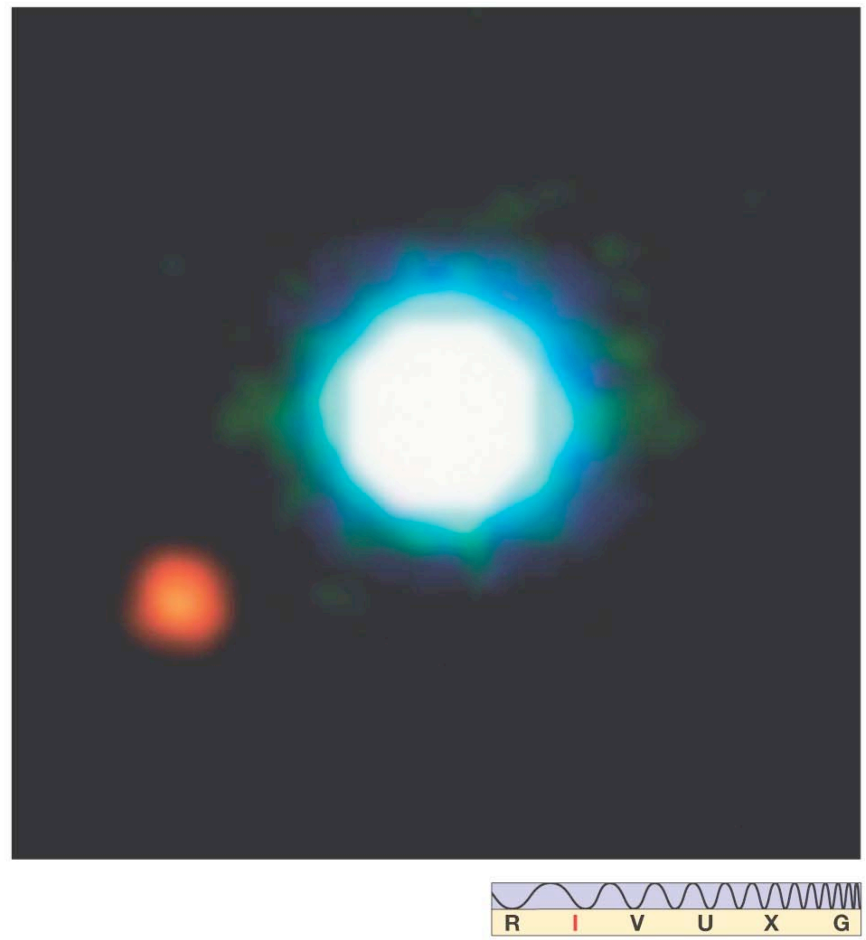
Direct detection of extrasolar planets is too difficult

Most extrasolar planets have been discovered ***indirectly***, through their gravitational or optical effects, and ***cannot be seen directly due to the glare of their star***.

This are a couple of exceptions: This star is a brown dwarf (ch.21), and the planet is clearly visible.

If you wanted to directly detect an extrasolar planet, what wavelength region should you look at?

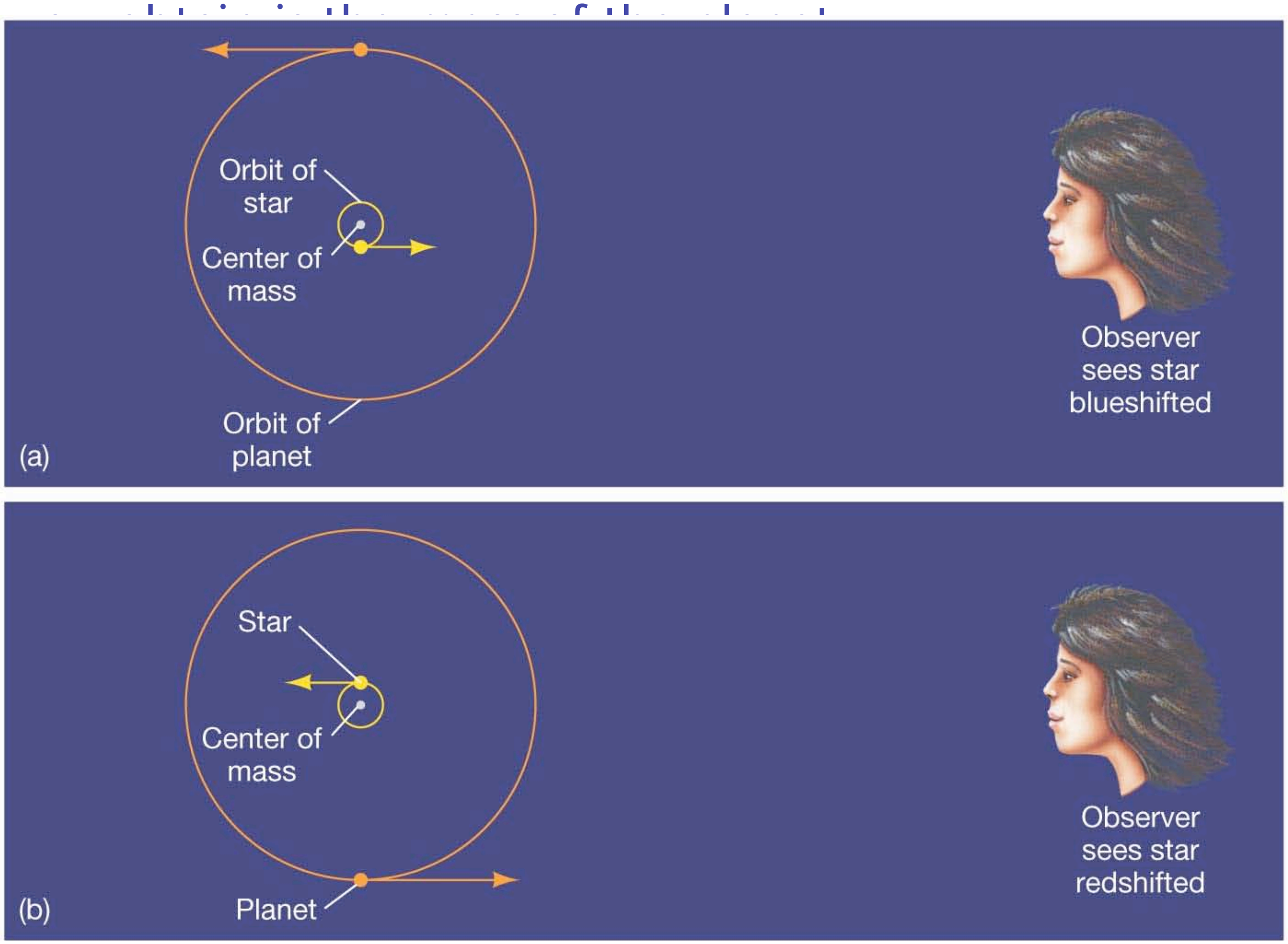
You should be able to explain why so difficult. (Two reasons.)



This would be called a "direct detection" and will continue to be rare, and only possible for massive planets, for (probably) decades.

Detection based on "wobble" of star produced by gravitational tug of the planet on the star

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. The magnitude of the wobble of the star depends on the gravitational tug, hence the mass, of the planet. Notice that all



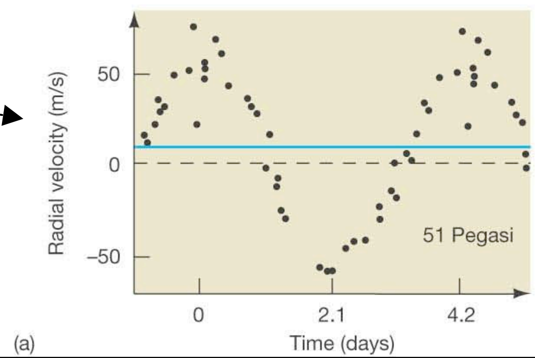
The radial velocity method:
Wobbles detected using spectral line Doppler shift

If the “wobble” is partly in our line of sight (i.e. there is a component away and toward us), it can also be detected through the Doppler shift as the star's motion changes. But the shifts should be *tiny*, and very difficult to detect, even for massive gas giants like Jupiter.

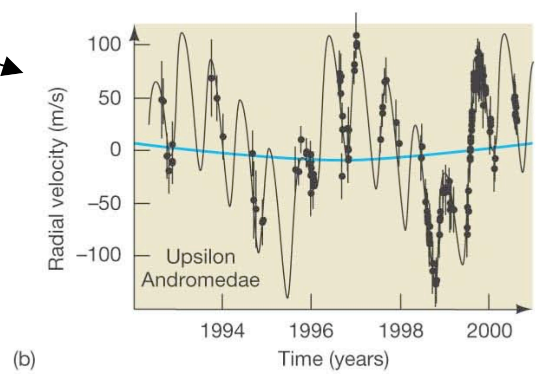
1995: Surprise! “Close-in” Jupiters, periods of days! Hot!!

These two graphs show radial velocity as a function of time: these stars are approaching, then receding from us.

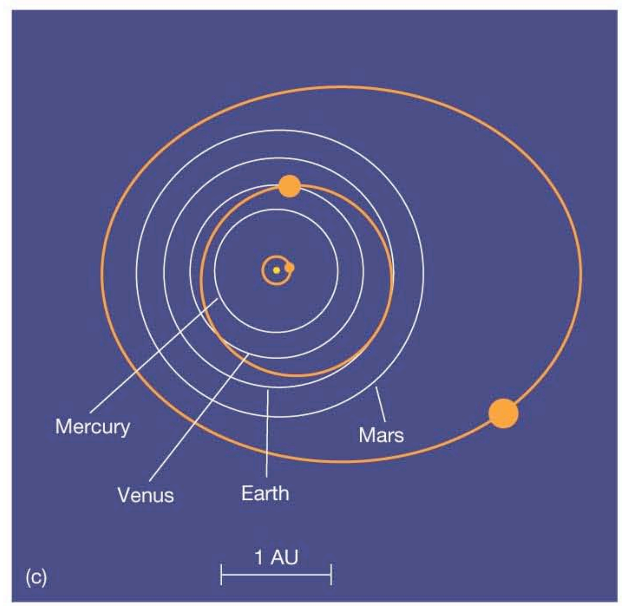
The first extrasolar planet discovered: 51 Pegasi



A multiple planet system: Upsilon Andromedae



Orbits of the three planets in Upsilon Andromedae



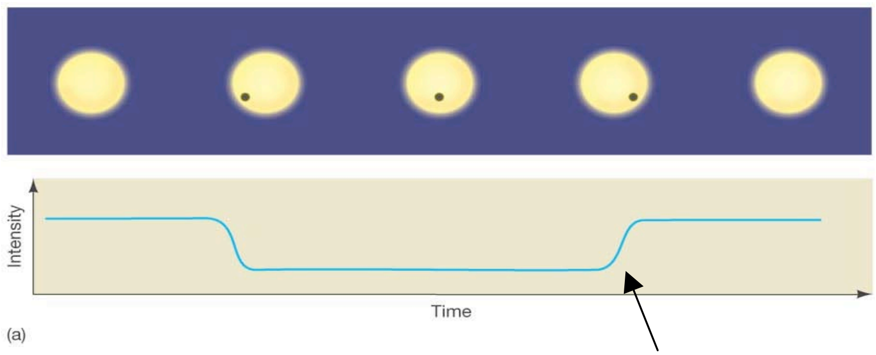
A different method for detecting planets: Transits

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, a (**very small**!) decrease in luminosity may be observed as a function of time. This is called a *transit*.

Notice a transit requires a planetary orbit almost perfectly in the line of sight of an observer on Earth. So transits will be found in only a tiny fraction of stars, even if all have planets.

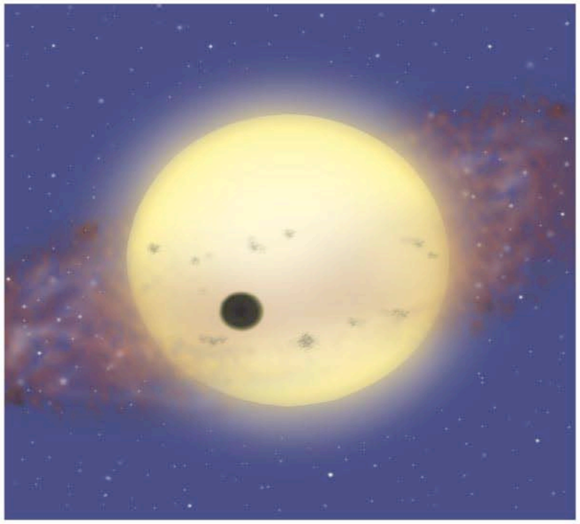
The time to enter and exit the "dip" in the light curve is a measure of the planet's diameter, so the transit method gives you the mass *and the density* of the planet! (Radial velocity method only gives the mass.)

Only a few planets have been discovered this way so far, but the transit monitor satellites COROT (European) and Kepler (U.S., launch in March) will change that by a huge margin, within a few years.



(a)

Brightness as function of time is called a "light curve." For most stars it would be constant, but with planets it may show variation of about 0.01to 0.1 percent: Difficult observational challenge.



(b)

Results so far (nearly all from radial velocity method)

- **Nearly all extrasolar planets have (so far) been discovered by radial velocity method.** Why? Because they are mostly planets orbiting close to their parent star, so moving fast, just what Doppler effect is sensitive to.

- **More than 300 extrasolar planets have been discovered so far, over 100 since the publication of the last edition of your textbook.**
Basic result: Much more variety than expected, mostly in orbital properties.

- **Most have masses comparable to Jupiter's (several hundred times the mass of the Earth).** *This is purely a selection effect because it is more difficult to detect smaller-mass planets--less effect on parent star's wobble (or fainter transit to detect--see later).* **But indications that there are many more low-mass planets to come. Current record is ~ 5 Earth masses.**

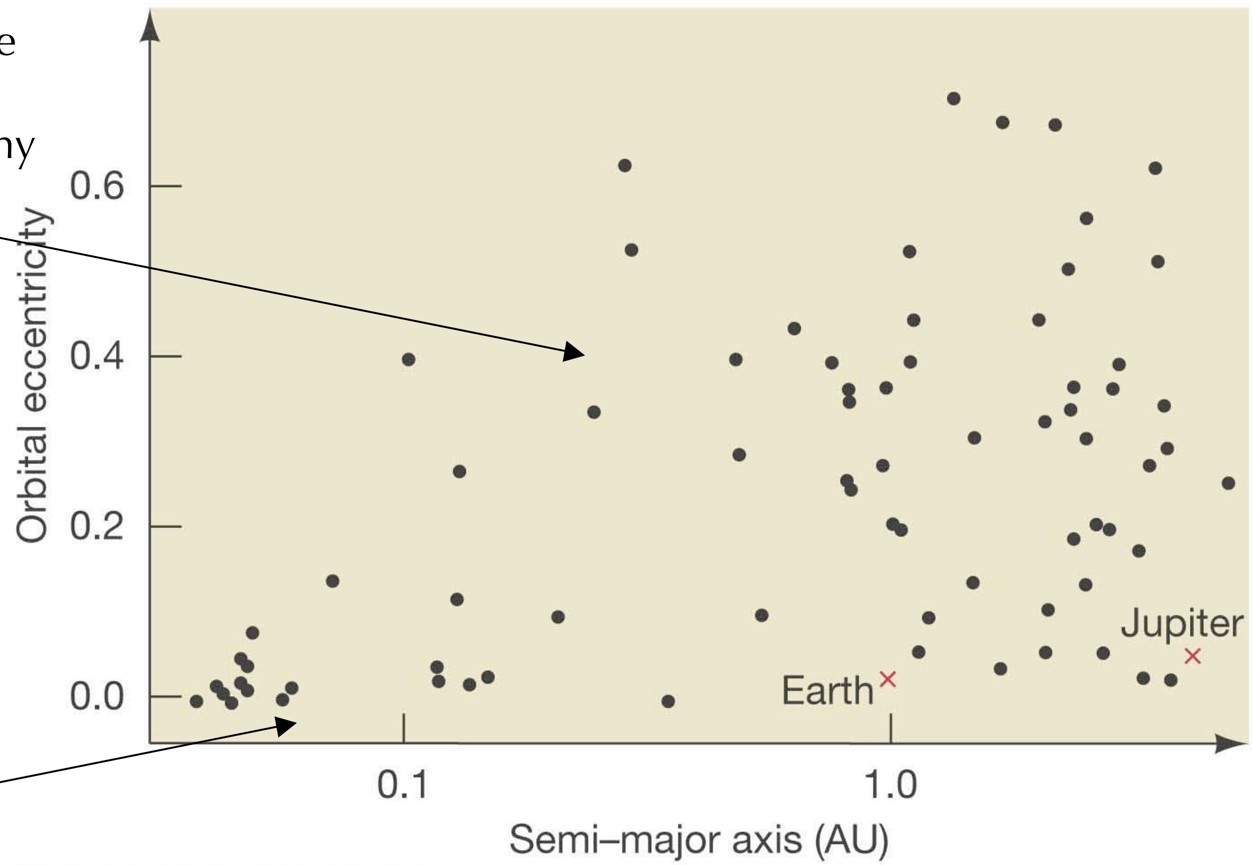
- **Orbits are generally much smaller, and in some cases very much smaller, than the orbit of Jupiter. *Almost* completely unexpected--theory of *migration* of protoplanets had been forgotten.**

- **Orbits have high eccentricity compared to solar system planets. This is *still* not understood.**

Orbits of extrasolar planets

This plot shows the semimajor axis and eccentricity for some of the known extrasolar planets, with Jupiter and Earth included for comparison. Knowing these are mostly Jupiter-class planets, notice how strange this diagram is compared to what we expected from our own solar system.

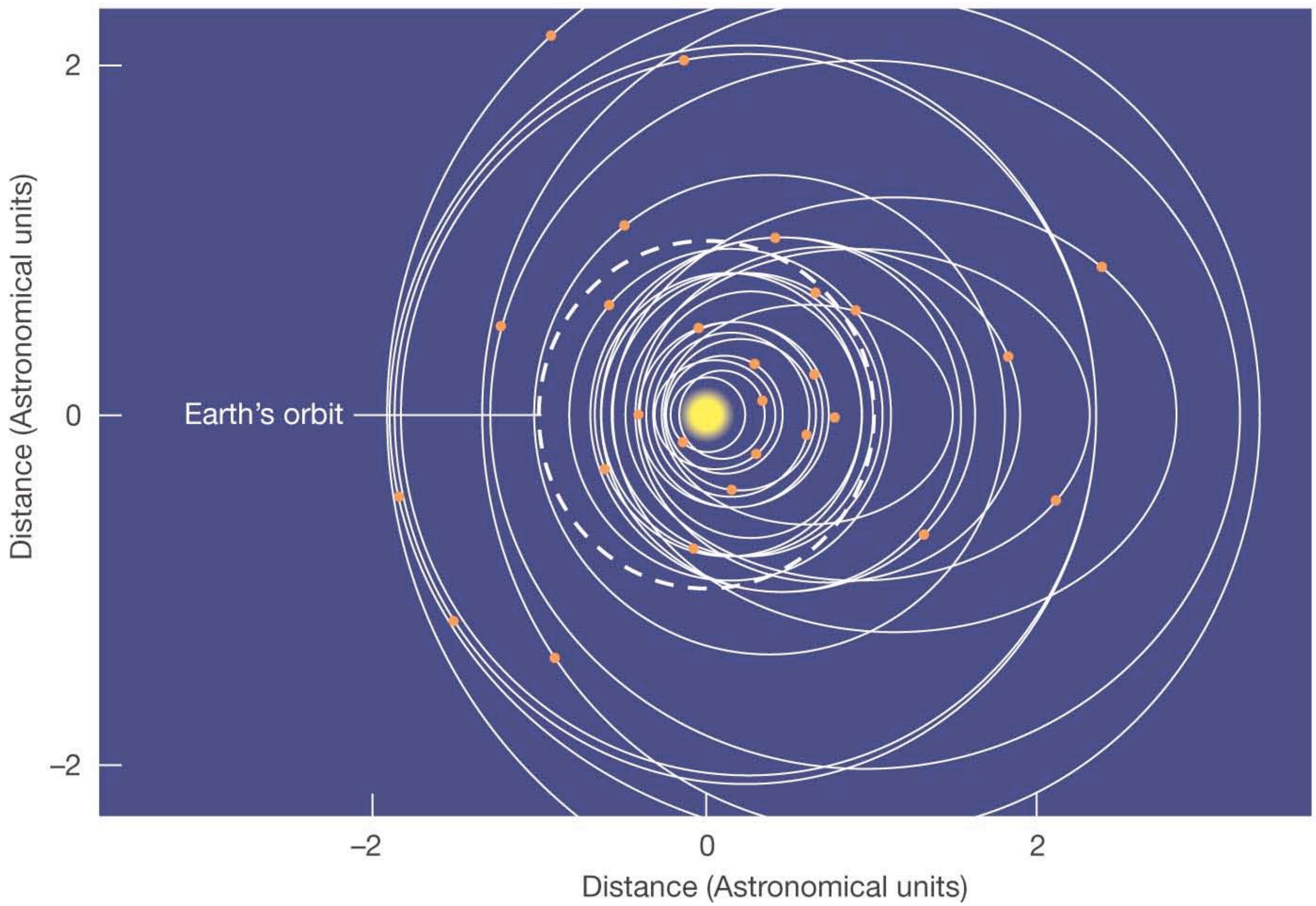
Planets in our system have nearly circular orbits with eccentricity near zero--why so many eccentric extrasolar planets?



Mercury is at 0.4AU.
Why so many close-in extrasolar planets, and none in our system?

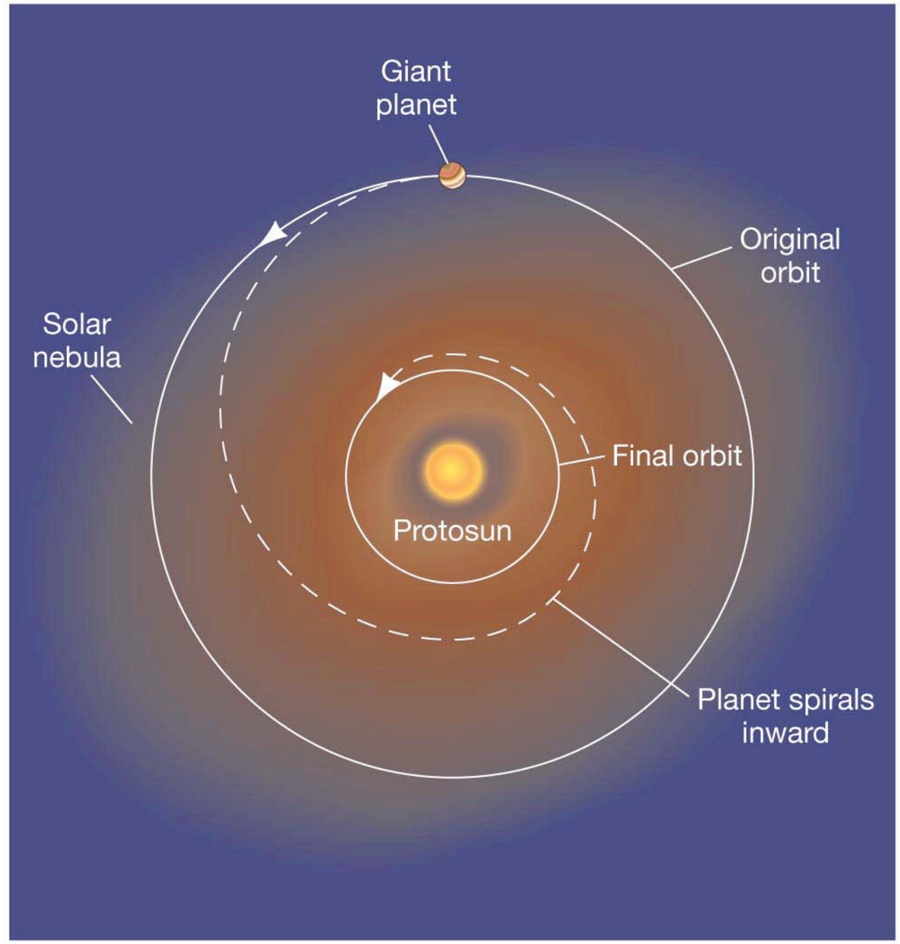
Orbits of extrasolar planets (continued)

Another way to see the strange results: Orbits of 60 of the known extrasolar planets. ***Note that some of them are very close to their star: These are called "close-in giant planets," because we expected giants (that's all we can detect) but we expected them out where Jupiter is!***



Sinking planets: Migration in young planetary systems

- Theories show that Jupiter-like planets can **migrate** inward, through friction with gas in the protoplanetary disk of the parent star.
- This process must take place early in the life of a planetary system, since we see no gas disks around stars older than about 5-10 million years.



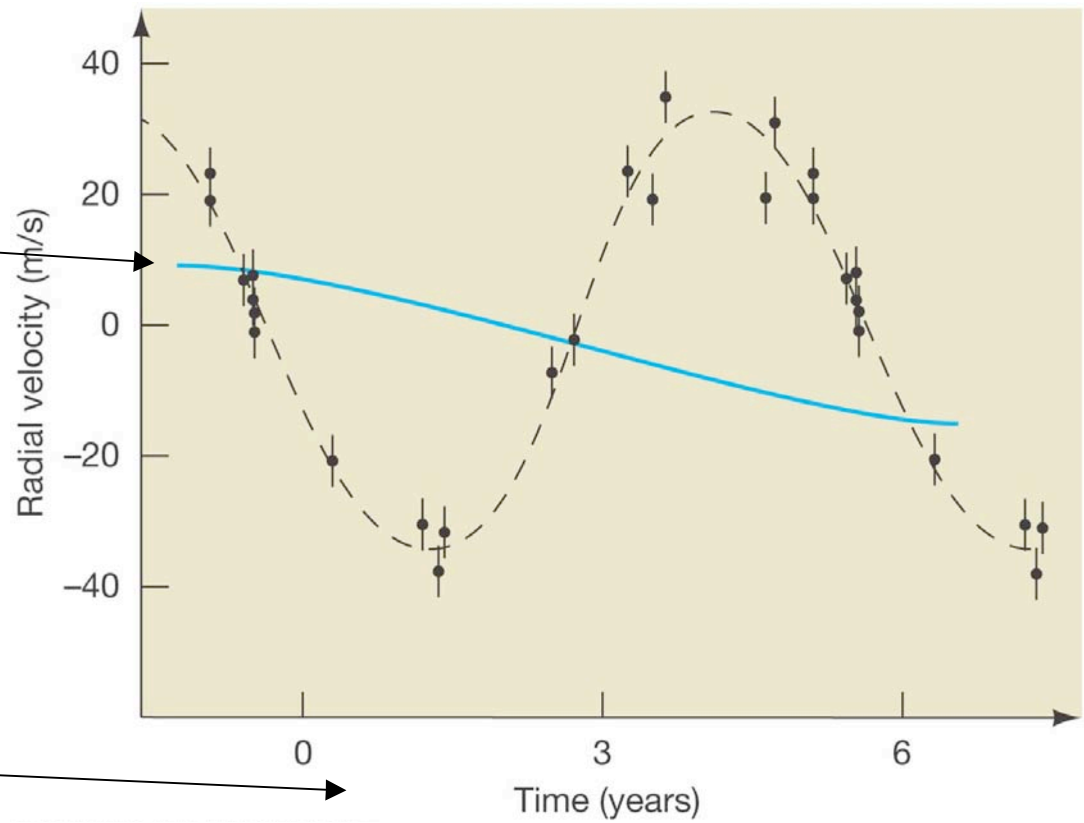
- Could an Earth-mass planet survive the passage of a migrating Jupiter? Could such a passage actually *assist* the formation of Earth-like planets??

Jupiter-like planetary orbits have been found

Recently, more Jupiter-like orbits have been found; this one has twice the mass of Jupiter and an orbital period of 6 years. You can see why it has taken so long to discover planets in Jupiter-like orbits: You have to observe for at least one orbital period.

It takes six years for this planet to orbit just once, and observers usually demand more than one orbit for confirmation.

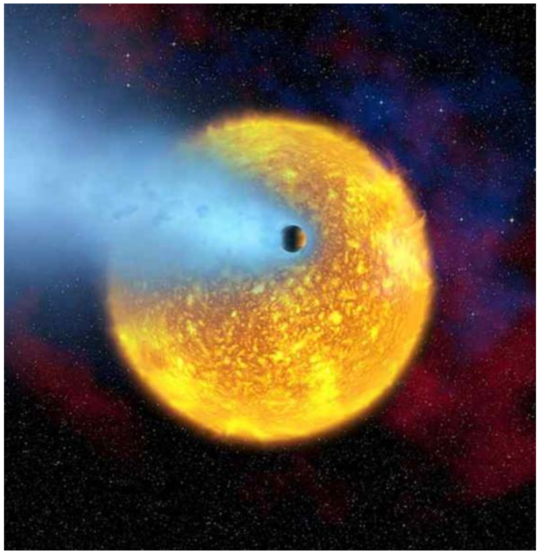
The blue line is the radial velocity curve for Jupiter. Notice how much more difficult its detection would be.



This represents about ten years of observations!

More results on extrasolar planets:

- Planets orbiting within 0.1 AU of their stars are called “hot Jupiters”; they are not included in the previous figure but are numerous. Some are vaporizing as they are cannibalized by their parent star. See illustration.



HD 209458 b (“Osiris”)
First transit discovery,
evaporating exoplanet

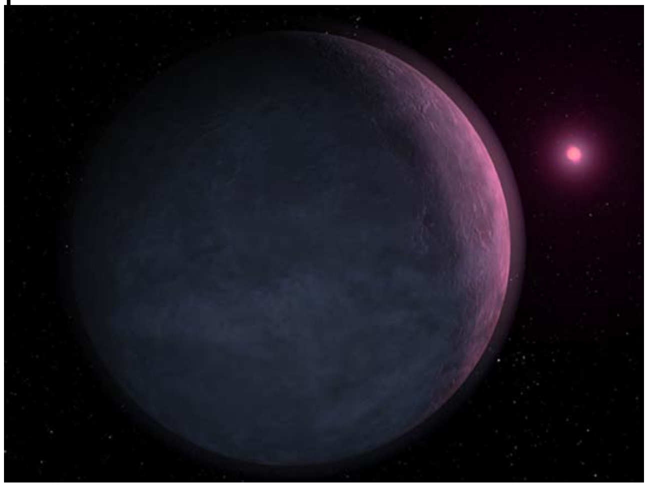
- Stars with composition like our Sun (about 1% elements heavier than helium, by mass) are found to be more likely to have planets than planets with fewer heavy elements, showing that the “dusty disk” theory is plausible.

Results, continued

- The number of lower-mass planets with larger periods continues to increase, pointing toward the possibility of a very large number of Earth-like planets, and solar system-like giant planets.
- **Recent (last five years) surprise**: detection of planets with masses like Neptune ("hot Neptunes," about 20 Earth masses), then "super-Earths" (about 5-10 Earth masses, probably rocky or ice), using radial velocity and other techniques. Lately: 2-3 Earth masses from COROT.
- The stage is set for discovery of an Earth-like planet!

Note: These are *not* real images!
Just "artists' conceptions."

Gliese 581c: 5 Earth masses, distance from star close to what is needed for liquid water



MOA-192b: 3.3 Earth masses. Current record holder, until last year.

15.7 Is Our Solar System Unusual?

Many of the other planetary systems discovered so far appear to be very different from our own--this came as a surprise. However many multi-planet systems are now known, and one system has two planets that resemble Jupiter and Saturn. (See earlier slide with a Jupiter-like orbit for reminder of why it takes so long to find these planets.)

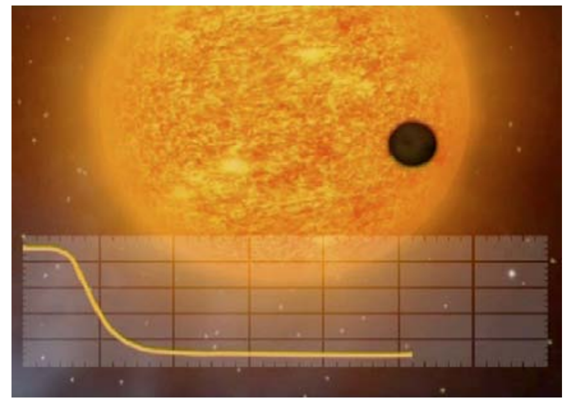
- **Selection effect** biases sample toward massive planets orbiting close to parent star; low-mass planets, or planets far from their star, would be very difficult to detect this way, at least from the ground. An example is on next slide.

- Best estimates are that about 20 percent of stars like Sun have Jupiter-class planets. In that sense we are unusual because we have *two* gas giant planets. But a significant fraction of systems with Jupiters have "close-in" hot Jupiters, not like ours. So with respect to giant planets, we appear to be an unusual system.

15.7 Is Our Solar System Unusual?

A substantial fraction of stars that have been measured have planets around them of the sort that can now be detected. They are mostly gas giants like Jupiter, but closer to star. ***Why didn't our Jupiter migrate?***

Nearly all of these have been discovered using the radial velocity method. This method (and most other methods) miss planets far from their stars, so can't tell how common systems like ours are.



The detection of Earth-like planets is the "holy grail" of planet detection. Earth-*mass* planets should be discovered soon from orbiting transit observatories **CoRoT** and **Kepler.**

The transit method involves looking for changes in a star's brightness as a planet passes across it. It requires planets whose orbits are nearly exactly lined up with our line of sight, so must detect *extremely* small changes in stellar light in only a tiny fraction of stars surveyed. This is why space observations are required.

Launch of transit detection missions **CoRoT** (2008) and **Kepler** (March 2009) marked new era: If Earth-like planets exist, these missions will find them, giving their mass *and* their density. That tells us if the planet is an iceball (lower density) or rocky (higher density). But not whether they have water, or life.

Summary of Chapter 15

• The solar system is orderly, not random; yet strong evidence for catastrophic collisions. Need formation theory that explains this.

• Condensation theory is the current favorite—large cloud of interstellar gas and dust starts to collapse, the Sun forms at the center, residual gas and dust remain in a rotating disk. Dust particles act as accretion nuclei to form the planets, by sticky collisions with other dust particles.

• Rocky planets would form close to the Sun; outer planets contain icy materials that would vaporize or escape at higher temperatures. Their cores grew massive enough to accrete gas in the disk before it got blown away (5-10 million years).

• Asteroids, comets,··· never condensed into a larger object, but may have delivered organic molecules and water to the Earth.

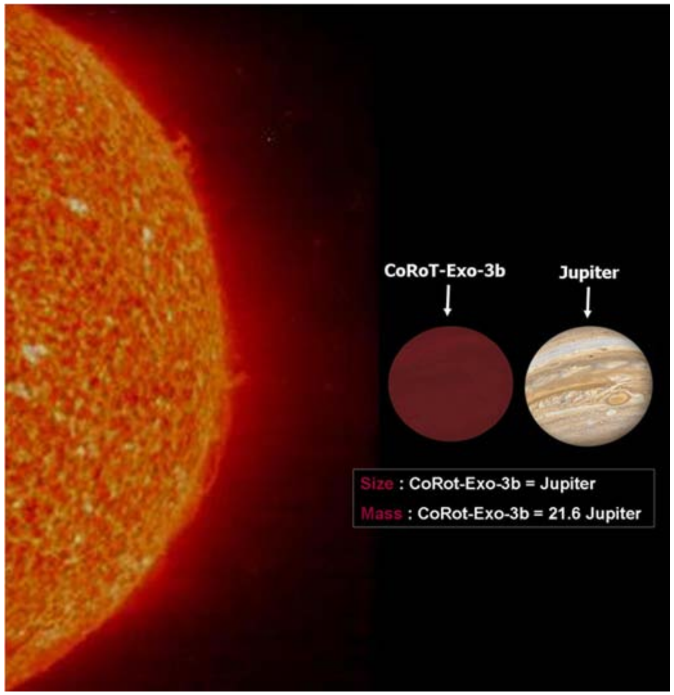
• Leftover planetesimals were ejected from the main solar system and are now in the *Kuiper belt* and the *Oort cloud*. Some occasionally enter the inner solar system as *comets*.

• Collisions during the growth of planets probably explain oddities of orbits and rotations of planets and moons, including formation of our own moon.

Summary of Chapter 15 (cont.)

• Over 300 extrasolar planets have been detected; most are massive and orbit close to their star. This is the result of selection bias, but still shows a possible fate that apparently did not occur in our solar system. Other systems, more like ours, are and will be discovered as longer periods can be observed.

• Further conclusions cannot be drawn until it is possible to detect terrestrial-like planets. CoRoT and Kepler will almost certainly find rocky planets with masses like Earth, but whether, for example, they have oceans or life remains at least a decade away.



This is just meant to remind you that the only thing we should expect is more weird surprises.