The Solar System (Ch. 6 in text)

We will skip from Ch. 6 to Ch. 15, only a survey of the solar system, the discovery of extrasolar planets (in more detail than the textbook), and the formation of planetary systems (also in somewhat more detail). No details on individual planets--but I suggest you flip through those chapters.

The solar system consists of the **Sun** (a typical star), orbited by 9 (now 8) **planets** (be able to name them!), about 40 **moons**, **asteroids**, and a large number of **comets**. Most of the objects have nearly circular (but still elliptical) orbits, but some (especially the comets) have extremely eccentric orbits. (Why?)

The sun is ~ 1000 times more massive than the rest of the solar system, and over 100,000 times more massive than the Earth, although it's radius is "only" about 100 times that of the Earth. For these reasons the Sun's gravity controls the motions of the other members of the solar system. (Think: Newton's law of gravity)

Planets:	Name	Distance from Sun	Satellites	Year	Day
	Mercury	0.4AU	0	0.2 yr	60 days
	Venus	|	0	0.6 yr	243 days*
	Earth	|	1	1 yr	1 day
	Mars	1.5	2	2 yr	1 day

<u>Terrestrial planets</u> are similar in size, mass, density, and composition (*rock and iron*)

Asteroid Belt—probably "failed planet"

Name	Distance from Sun	Satellites	Year	Day
Jupiter (largest)	5	70?	12 yr	10 hr
Saturn (rings)	10	35?	30 yr	
Uranus	20	30?	80 yr	*
Neptune	30	15?	160 yr	

<u>Giant (or Jovian, or gas giant) planets</u> are larger, *much more massive*, much *lower density* (showing they are composed of lighter elements, especially large amounts of hydrogen. Belted weather systems (most famous feature: Jupiter's "Great Red Spot").

Pluto	40 AU	1	~250 yr	*

* means peculiar orbit or rotation.

--> 2006: Pluto demoted to non-planet status.

Notice that ***a few objects have peculiar orbits and rotation***; e.g. Venus, Neptune, Pluto,… This suggests collisions with other large "planetesimals" when solar system was forming. They are crucial clues to the formation of our solar system.

The most important thing to remember is the differences in properties between the ***terrestrial planets*** and ***jovian planets***, as summarized in Table 6.2 (p. 150). Those are also big clues about how the solar system formed, so you should remember them when you read Ch. 15.

<u>Comets</u>: Iceballs, most in highly eccentric orbits which extend far beyond Pluto. Spend most of their time far from sun (in the "***Oort cloud***"; also the "***Kuiper belt***" comets outside of Neptune's orbit).

Comets and ***asteroids*** are "debris", but very important because they represent the solar system when it was first forming. Also, *they may have delivered the organic compounds used to produce biological molecules on the early Earth*. (Might be difficult to produce them on the Earth itself, although controversy about this.)

<u>Age of solar system</u>: From radioactive decay ages of meteorites and moon rocks: 4.6 x 10^9 yr (about ***4 or 5 billion years*** is good enough for memory).

Remember that sec. 6.6 (Spacecraft exploration of the solar system) is for your own interest, but will not be on the next exam. The only exception is the question below.

<u>Homework problem</u>: Why was the discovery of methane gas (NH_3) in the Martian atmosphere a couple of years ago exciting, and what was the resulting controversy about its interpretation?

Formation of Planetary Systems (ch. 15)

This has become one of the most exciting fields in astronomy because since 1995 about 180 planets outside our solar system have been discovered (sec. 15.5), severely challenging theories of the origin of planetary systems, and opening the tantalizing possibility of discovering **earth-like worlds** in the future. We cover this in later notes, but it is not reflected in as much detail in your book.

Chap. 15 of the text gives an excellent discussion of the theory, so only brief outline here.

Clues:

<u>Regularities</u>--orbital shapes and planes; spin directions of planets and moons; "differentiation" (difference in chemical composition) between terrestrial and Jovian planets.

<u>Irregularities</u>—Unusual planet and satellite rotations (Venus, Uranus, Pluto).

Also: cratering history of planets and especially the moon (preserved because no erosion). (When you see this later, you should know why this is an important clue!)

Theory almost universally accepted: Stars form by gravitational contraction of gas clouds (Fig. 15.1).

A contracting *rotating* object will spin faster as it contracts (conservation of "angular momentum") and *flatten* into a ***disk*** $\Rightarrow$ "protosun" surrounded by rotating <u>**disk**</u> or "protosolar nebula" ("protostar" and "protostellar" for other stars). See Fig. 15.1 for general cartoon, Fig. 15.2 for an image of a couple of disks around young stars; more are shown below--notice how they can be detected by excess radiation of a certain wavelength. For stars younger than a few million years, almost all the stars like our sun, or less massive than the sun, appear to have disks of dust and gas around them.

So by now can make a strong case that young stars have rotating disks—the question is just about whether and how that disk turns into planets.

The standard picture to get the process started: Microscopic dust grains (about 1% by mass) grow by <u>collisions</u> with other grains. Snowball effect called "accretion" (meaning accelerated collisional growth here) leads to growth of larger bodies called "planetesimals" (ranging from large rocks to small moons in size).

See Fig. 15.3. There is some debate over whether collisions dominate or whether they lead to growth at all.as

<u>More collisions:</u>

<u>Slow-speed collisions</u>: Merging, "coagulation", and "accumulation" of planetesimals into planets (note that this is sometimes called "accretion" in your text). Either get terrestrial-like planets (if close to the star, where it's too warm for "volatiles" to be solid or liquid) or Jovian-type planets (further from star, where cooler, so "accretion" of H-rich gas can occur on top of core—this is accretion of gas, not particle collisions).

Important to understand the dependence of composition of the inner vs. outer planets in terms of the temperatures at which icy ("volatiles") and rocky or iron solids could condense or be vaporized.

Intense study of Fig. 15.6 is recommended.

Jovian planets could have also formed by <u>direct gravitational instability of the disk</u>, with no accretion at all. In this case they would have only taken about 1000 years to form (see Fig. 15.5). In this case no collisional growth of a core, followed by accretion of gas, is needed. But some evidence Jupiter has a core, and the question of whether a protoplanetary disk can become unstable this way is unsettled.

<u>High-speed collisions</u>: fragmentation of planetesimals; these "leftovers" either bombarded the planets and their moons (see our Moon) or underwent gravitational encounters with young planets (not direct collisions) and became asteroids or comets. (See sec. 15.4 for a good list of unusual objects in our solar system that can be explained by catastrophic high-speed collisions. We will briefly discuss in class.)

Be sure to read sec. 15.3 on the Asteroid Belt, and on Comets and the Kuiper Belt. This process of ejection of planetesimals (and maybe even some planets) to form the Kuiper Belt and Oort cloud (or even escape completely) is extremely important (see Fig. 15.7).

The remaining debris of gas and dust that *wasn't* incorporated into a planet or other body was probably swept out of the forming planetary system by the intense <u>stellar winds</u> that are observed around all young stars. (See Fig. 15.4) But some solid particles were "left over," since we now know of many "debris disks" around older stars.

The whole process probably took 10 to100 million years, although this is wildly uncertain. The main thing that is certain is that the formation time was very short compared to the age of our solar system (about 4.5 Gyr = 4.5 billion years = 4500 million years). And it is now known that the gas and dust grains started to disappear within about 5-10 million years, so giant planets had to form faster than this (think: why?)

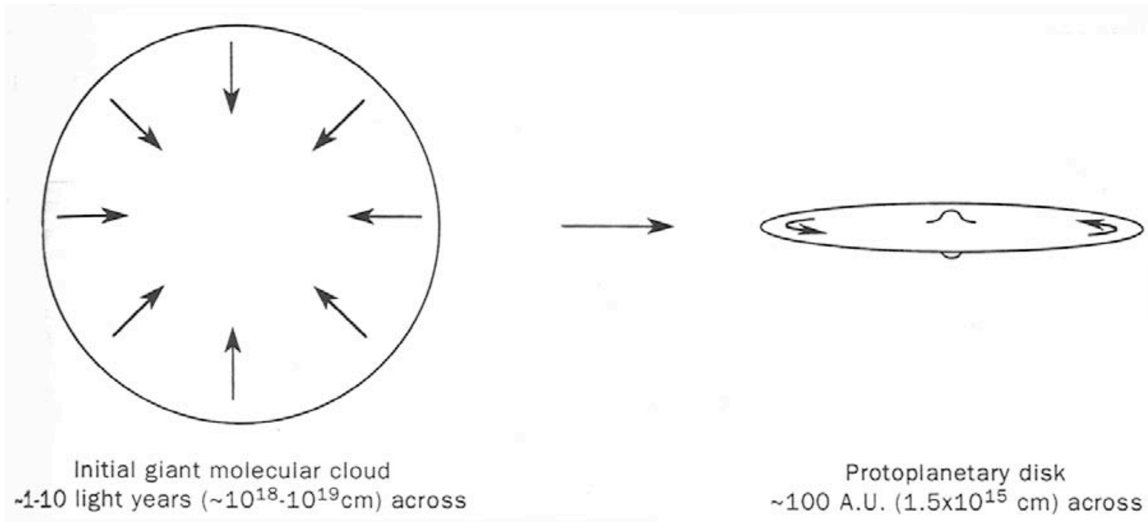
Notice that there are two types of planetary "migration" briefly discussed:

1. Early migration of giant planets due to interactions with other forming giant planets and the disk itself (p. 338; we will see there is evidence for this in extrasolar planets), and

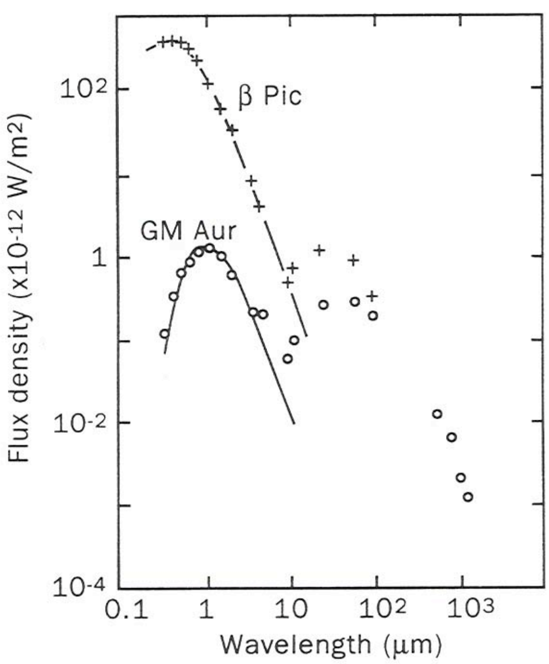
2. Later migration due to the interactions that eject planetesimals (pp. 391-392).

Common feature of all models for formation of planets:

Collapsing, *rotating*, gas cloud becomes a disk with star at center.



Evidence for disks: Infrared excesses in spectra of very young stars



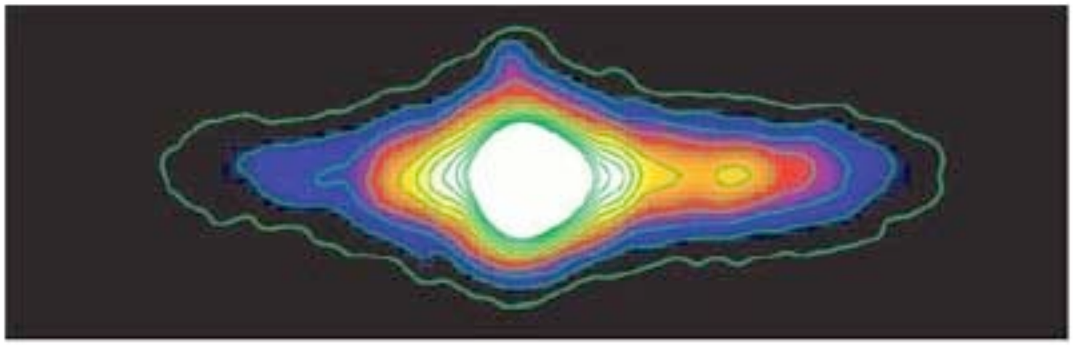
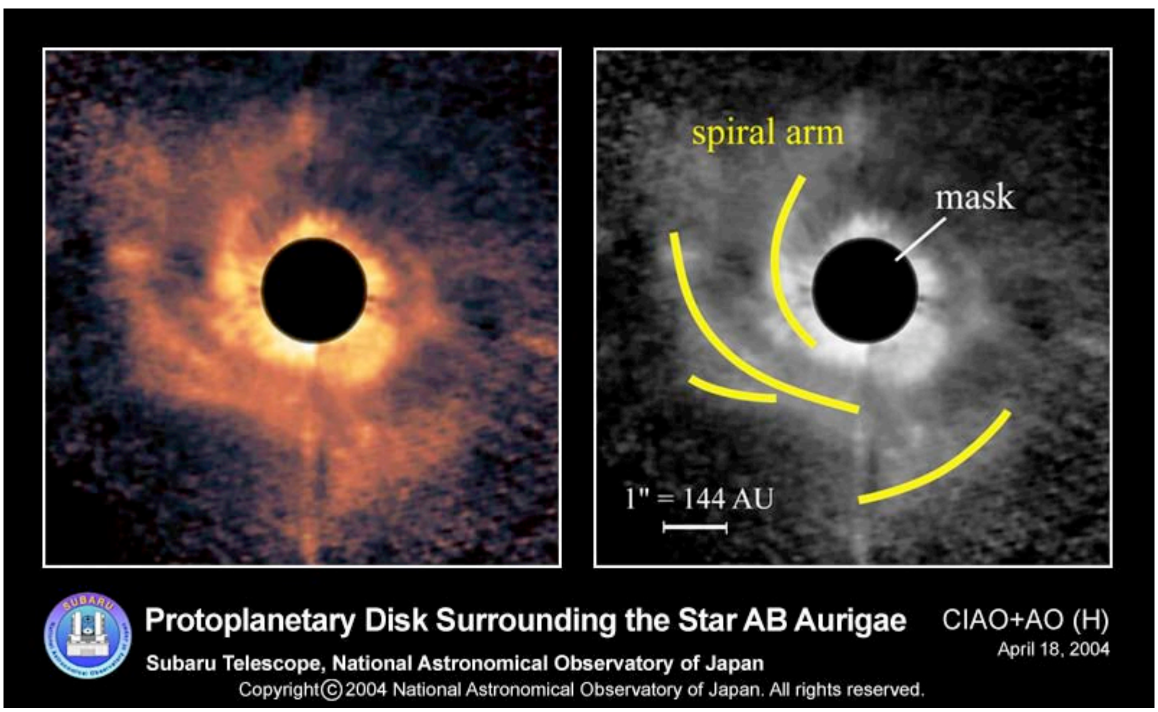
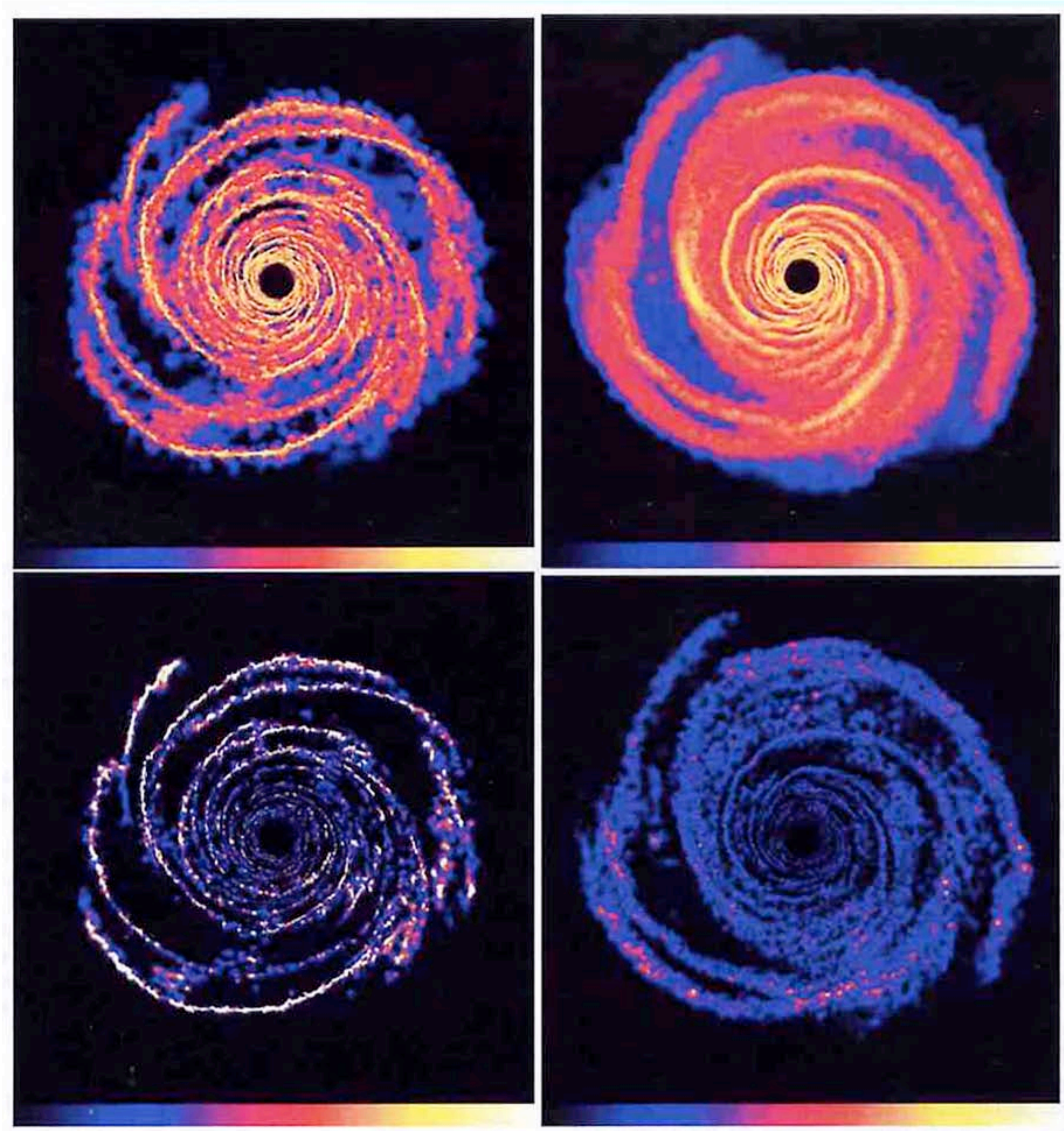


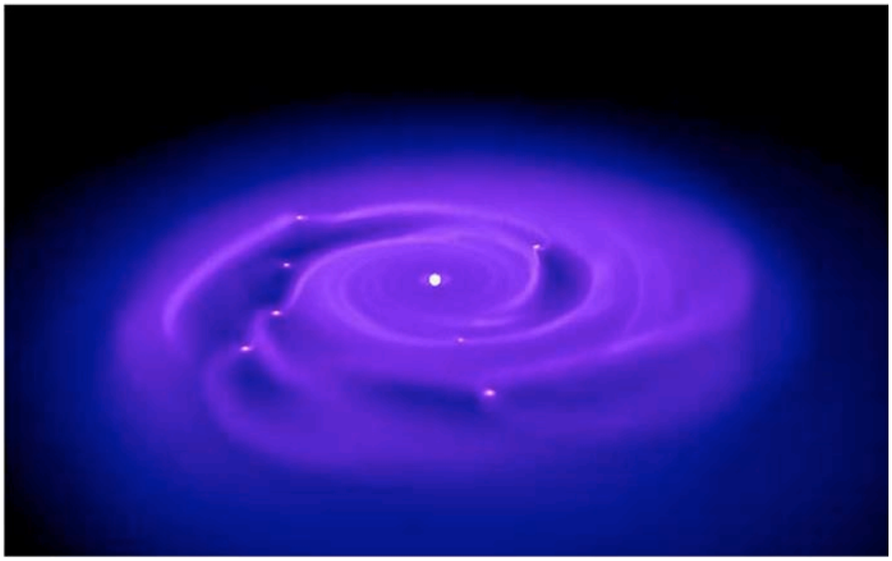
Figure 1 The β Pic disk, imaged in the mid-infrared at 11.7 μm

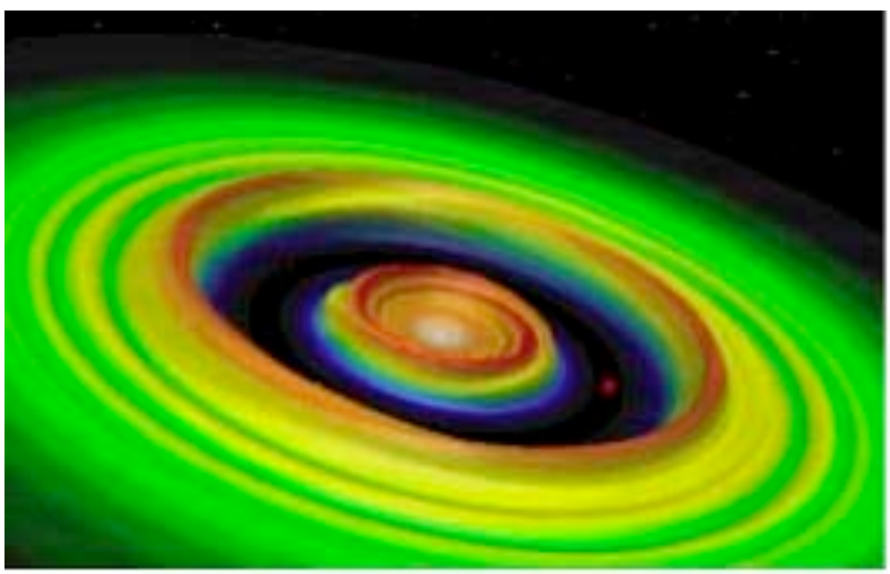




Computer simulation of gas and dust grains in a protostellar disk, for different size grains. Note how grains can be accumulated in the spiral waves (lower left).

Presence of planets can open up "gaps" in disks—indirect way to detect (giant) planets!



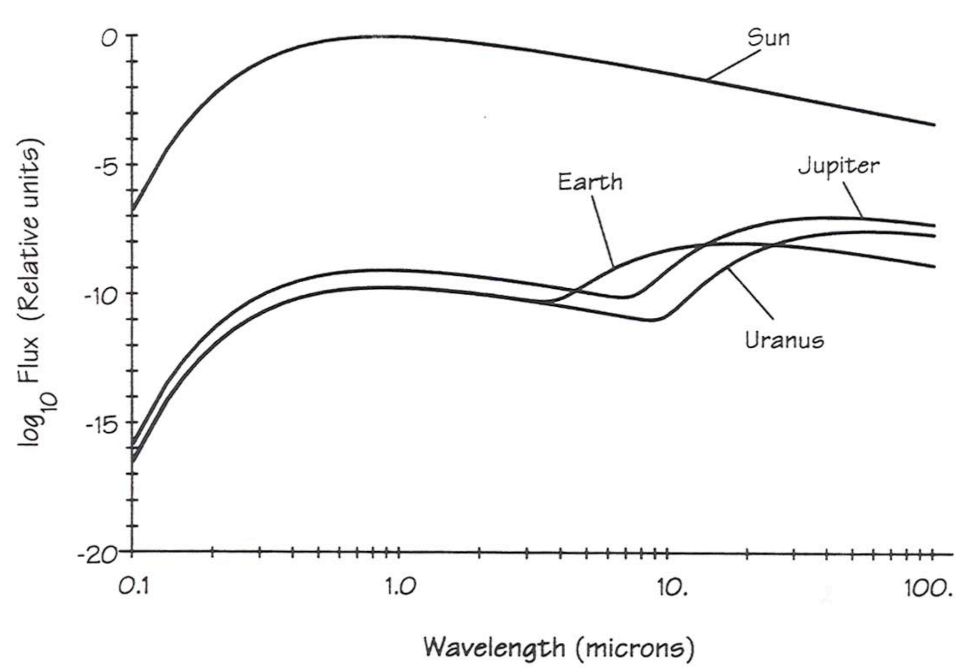


Bryden et al. 1999

Extrasolar Planets (sec. 15.5, 15.6)

Formerly the "holy grail" of astronomers, since 1995 about 100 planets orbiting stars other than the sun have been discovered. There are several techniques available, but we'll just discuss a few.

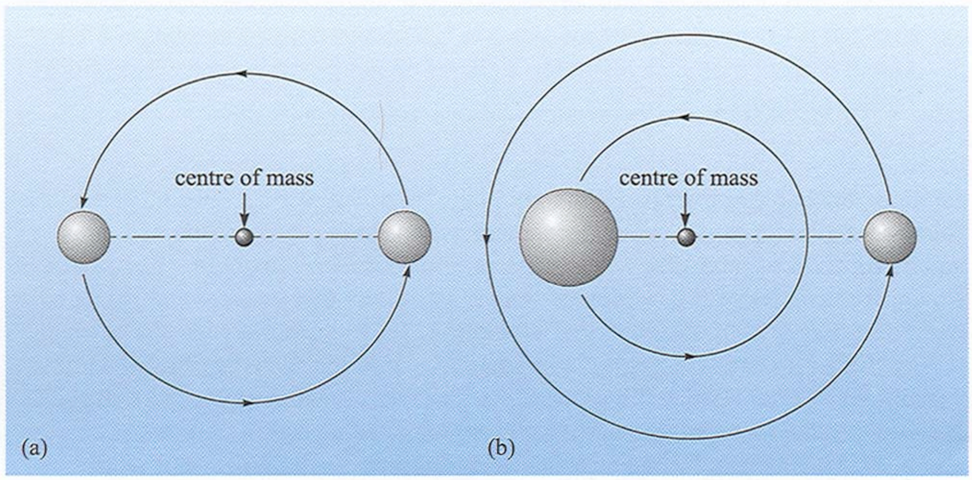
1. Direct detection—not possible at present. Reflected light from planet is about a billion times less than that of the star (less in the infrared, but still about a million or more—see illustration below), and the distance from the planet to the star (in angular separation) is so small that we can't resolve any planets if they are there. It may be possible to directly detect giant planets around very faint stars, but certainly not terrestrial-like planets.



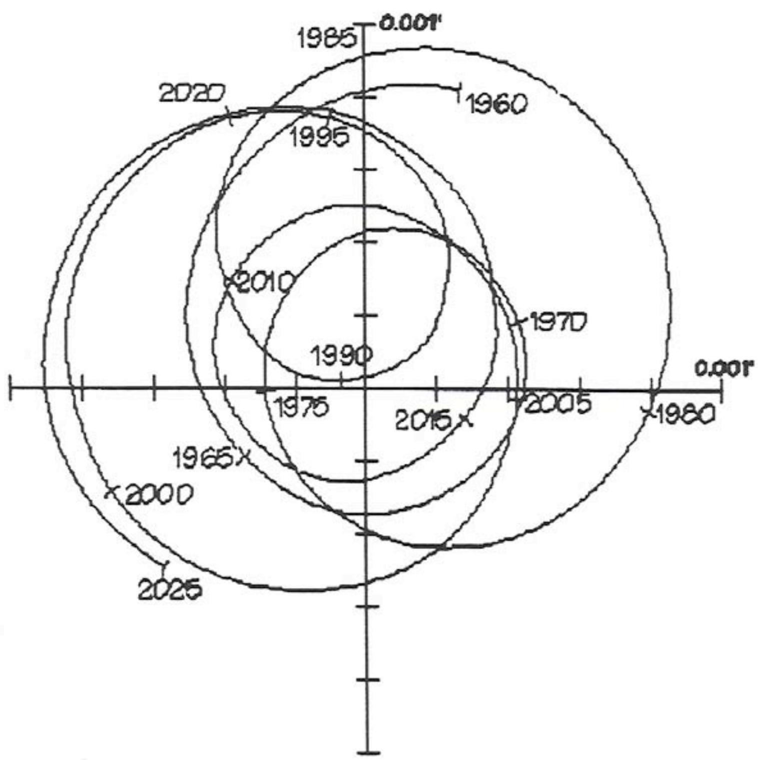
The spectral energy distributions of the Sun, Jupiter, Earth, and Uranus as they would appear at 5 pc, averaged over a 10% spectral bandpass. Note the decreased ratio of solar to planetary flux in the thermal infrared, compared to visible wavelengths.

This will have to wait for space-borne optical interferometers (Terrestrial Planet Finder/Darwin), which *might* occur around 2010.

2. Detect **wobbles** in the *star's* motion due to the planet's gravitational perturbations.



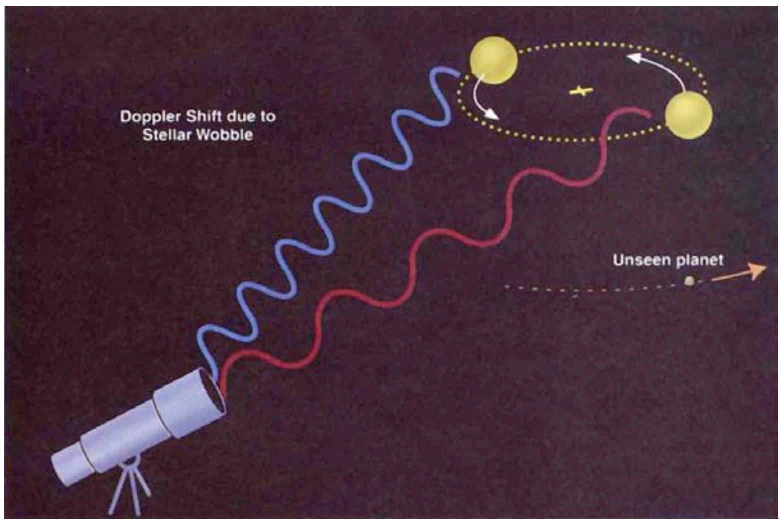
The orbits of a two-body system, showing the centre of mass in each case, for (a) two equal masses; (b) one mass greater than the other.

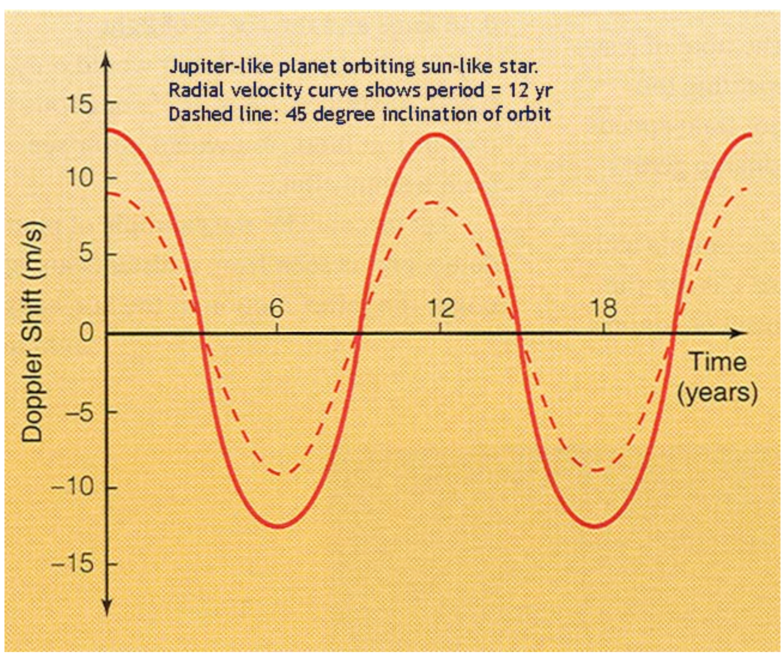


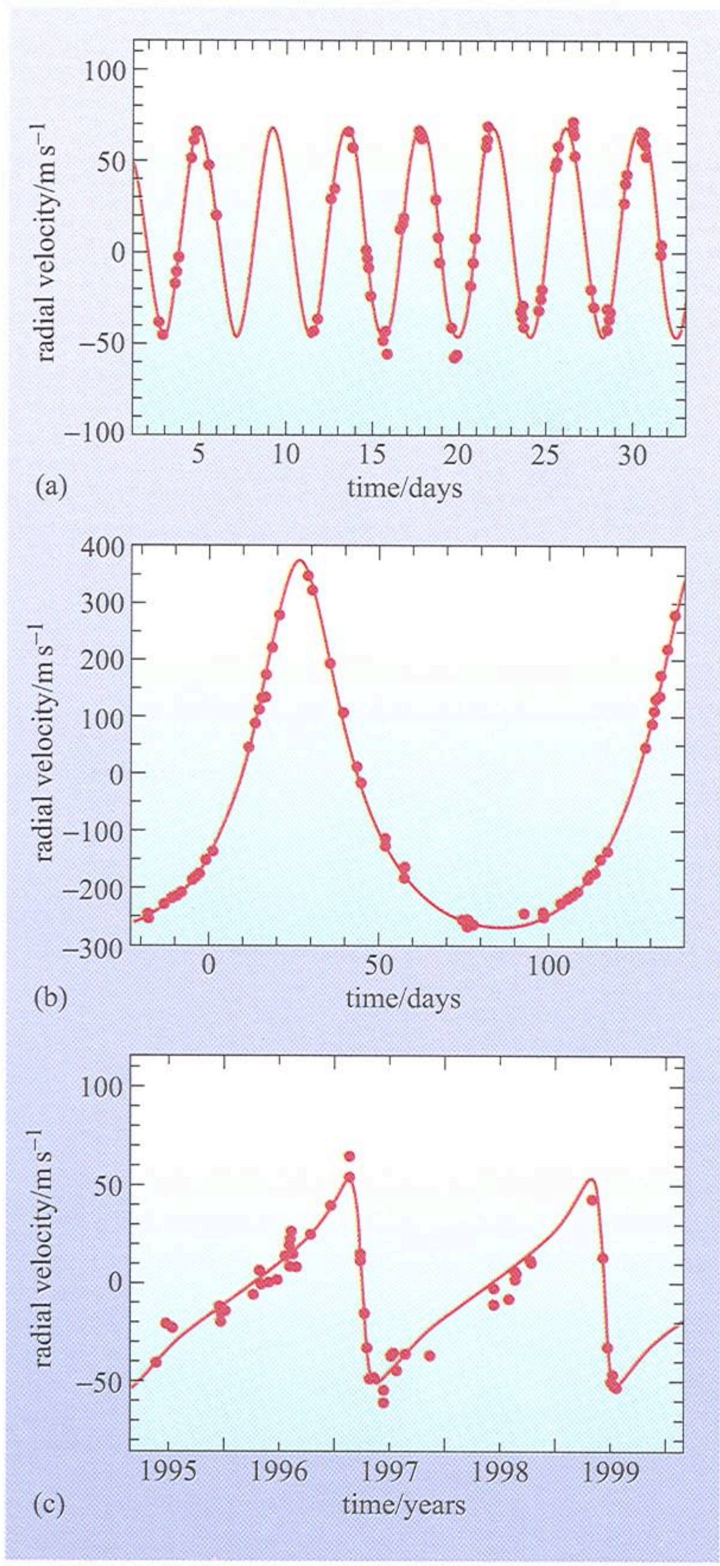
Sun's wobble if observed from a nearby star, over 50 years.

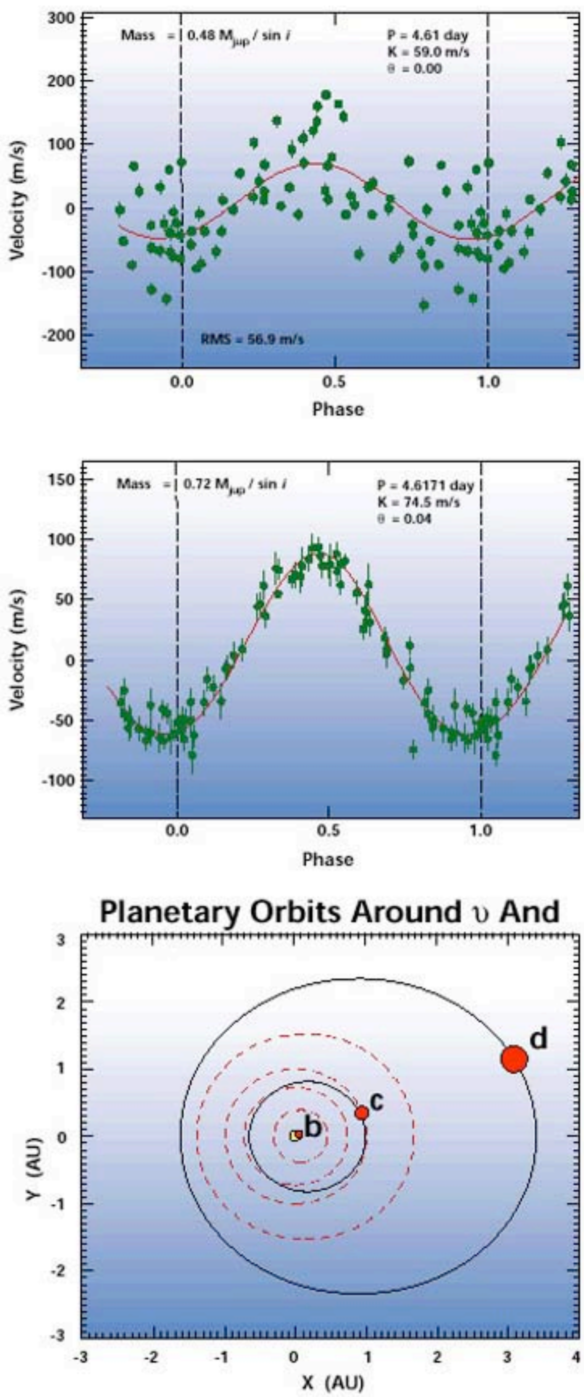
Two methods using stellar wobble:

A. **Radial velocity method**—radial velocity of star varies by a small amount as it wobbles (depending on its orientation to the observer). So search for *periodic* small radial velocity changes in nearby (bright, so you can get good spectra) solar-like stars. Size of velocity change indicates mass of the invisible planet.






radial velocity/m s^{-1}
100
50
0
−50
−100
5
10
15
20
25
30
(a)
time/days
radial velocity/m s^{-1}
400
300
200
100
0
−100
−200
−300
0
50
100
(b)
time/days
radial velocity/m s^{-1}
100
50
0
−50
1995
1996
1997
1998
1999
(c)
time/years



Radial velocity measurements have been used to infer the presence of multiple planets orbiting Upsilon Andromedae. The fit to the data for a single planet is relatively poor (top), while the fit for each planet is improved when the presence of three planets is taken into account (middle). Planets B, C, and D have orbital distances of 0.06, 0.85 and 2.5 AU, and Msin i of 0.73, 1.95 and 4.1 M_J, respectively (bottom). The orbits of the inner planets of our solar system are shown as dotted lines (Butler et al. 1999).

Nearly all planets discovered so far have been discovered by this technique.

Best for close-in (so short period, high velocity) massive planets.

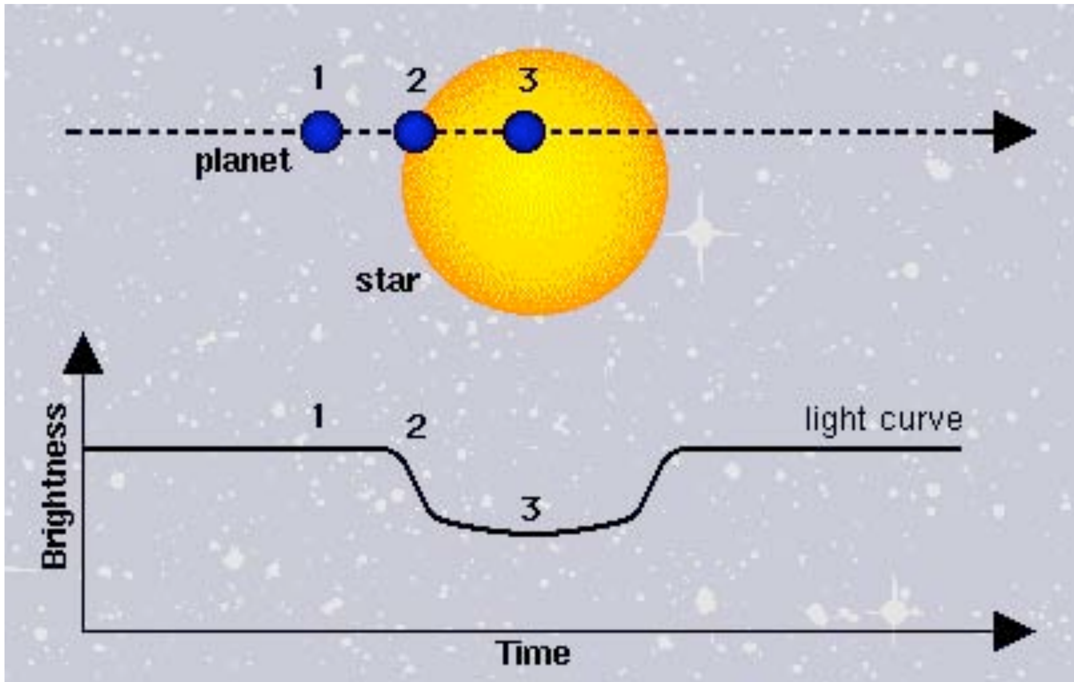
B. **Astrometric method**—search for periodic motions of the star in the plane of the sky, detecting the "wobble" directly. Size of the angular variation depends of the mass of the invisible planet.

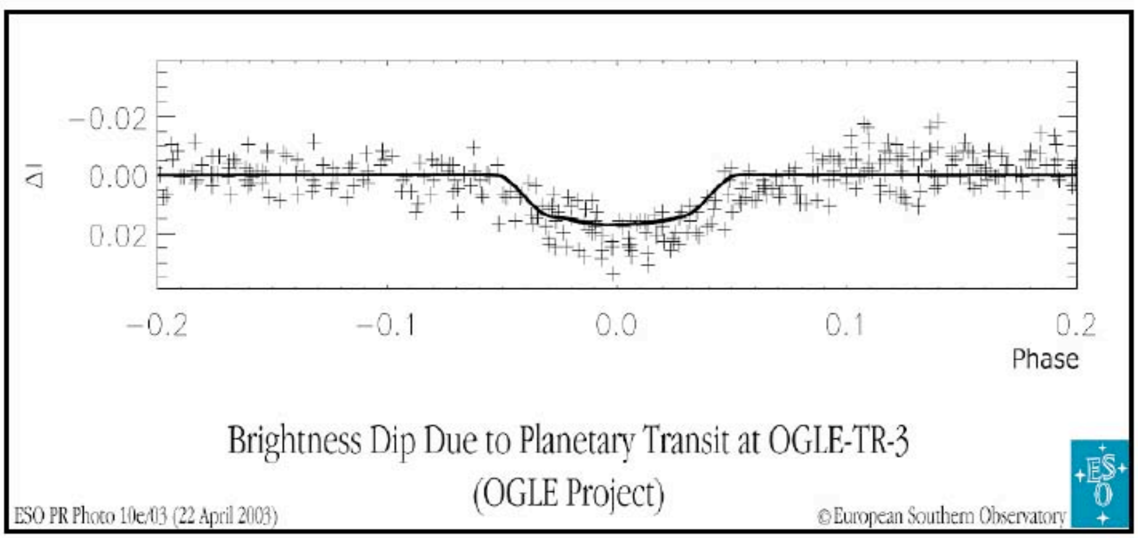
Works best for massive planets far from star (so center of mass is located further from center of star, so larger angular wobble—think about it; we'll discuss in class). The problem is that such planets will have very long periods (many years), so it requires decades for a detection. So far a few planets have been found this way, but it had already been discovered by radial velocity technique.

3. Transits (eclipses)—this is the most active approach at present, with over 30 groups trying varying strategies, and a major space mission ("Kepler") planned for the near future. Read about Kepler on p. 399.

The idea is to watch the light of the star very slightly decline if a planet in orbit passes in front of the star. (See "light curve" in Fig. 15.10.) You can get a *lot* more information about the planet using this technique than from radial velocity alone, but you have to monitor many 1000s of stars because the probability of detection is tiny (think about the orbit you need for a transit).

So far a few planets have been recently detected by transits (and then verified by radial velocity measurements).





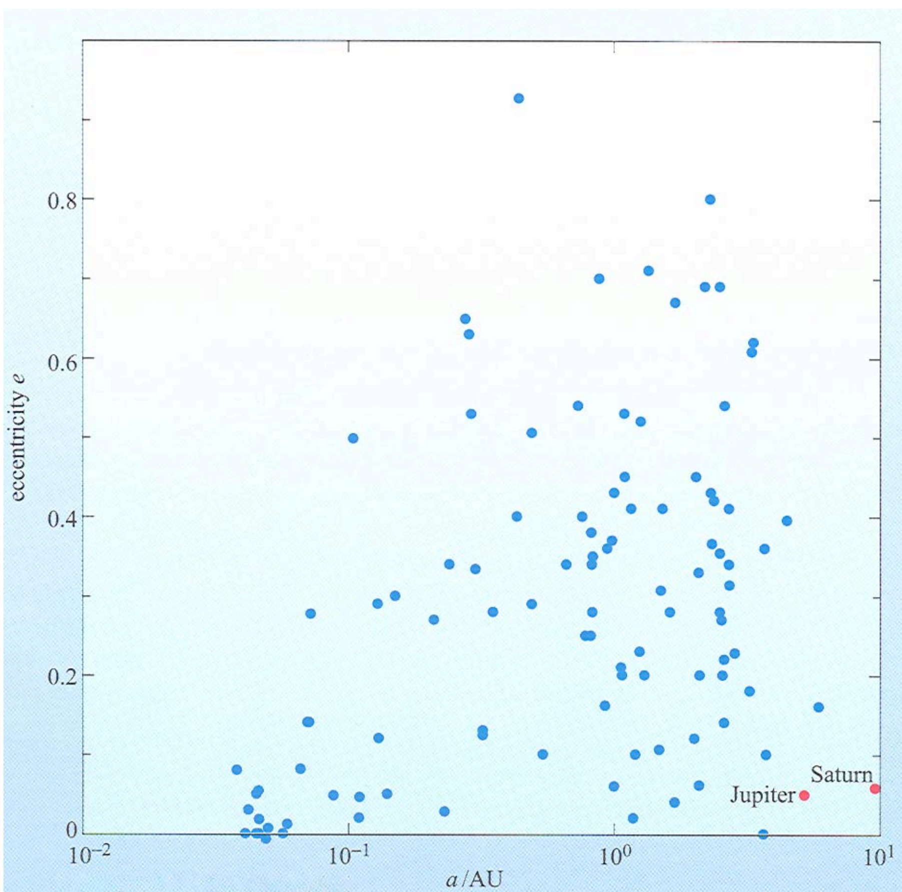
Folded photometry of the star, OGLE-TR-3 showing the small decrease due to the planet transit.

Surprises from the 140 or so planets discovered so far:

Giant planets usually very close to parent star: migration and cannibalism! (Will explain in class.) But some more distant (see Fig. 15.11).

This is partly a *selection effect*, because the radial velocity method gets its strongest signals from close-in planets, but still, no one expected to see "Jupiters" closer to their parent star than Mercury is to the Sun! Perhaps most planetary systems get devoured by their parent star before the system is cleared of the debris responsible for the migration. This might suggest that life is rare in our Galaxy!

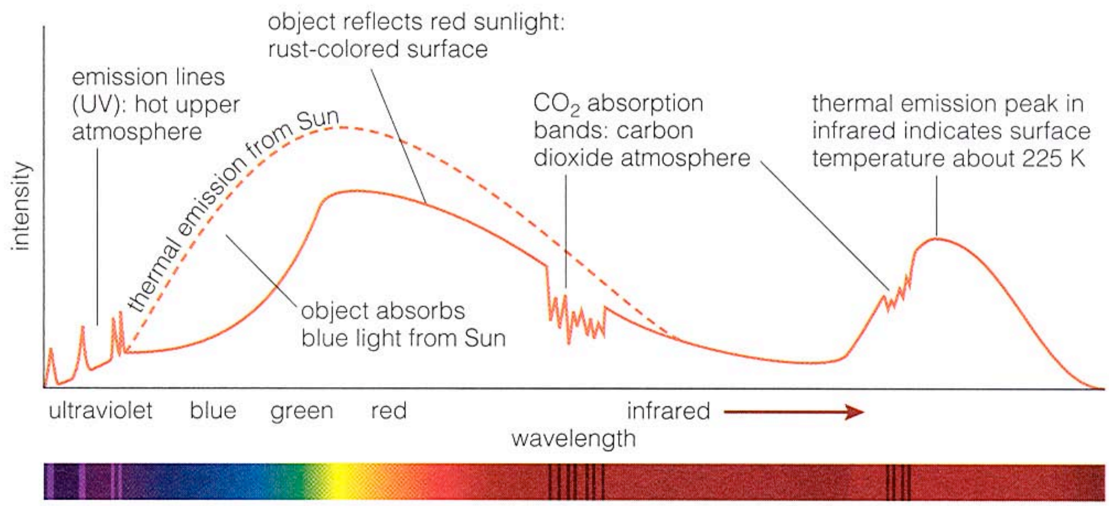
Some orbits fairly elliptical! (Compare: solar system orbits are nearly circular; see Figs. 15.11, 15.12.) How could this be? (See p. 398).



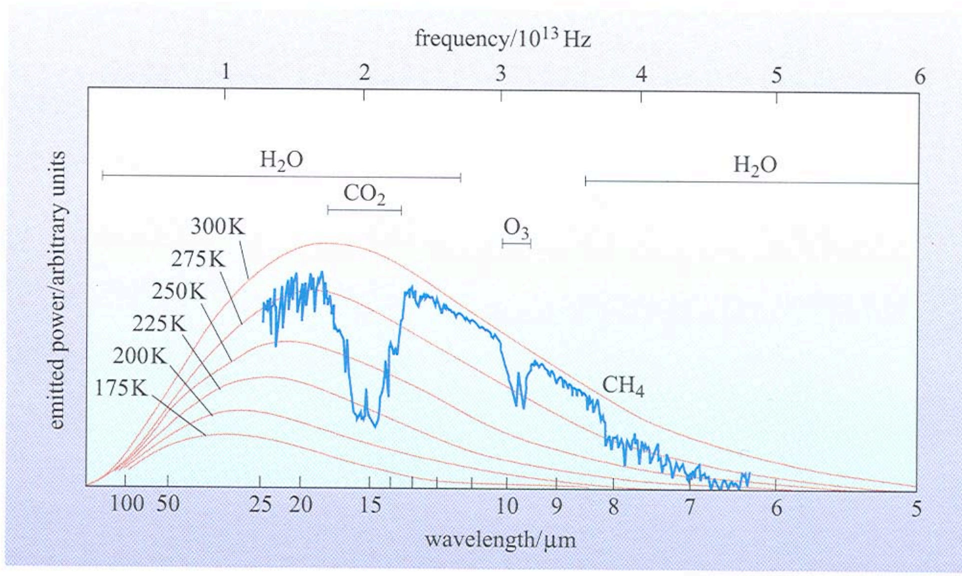
Homework question: Almost all of the extrasolar planets have masses similar to Jupiter or a little smaller—so probably gas giants. Within the past few months, what discoveries have been made that have changed the situation? What method did these discoveries use? Why are they so interesting?

Detecting other Earth-like planets? Will have to wait for transit sensitivity of Kepler space mission (launch~2007, read p. 399), or, for imaging and spectroscopic "biomarkers," the "Terrestrial Planet Finder" TPF mission around 2012.

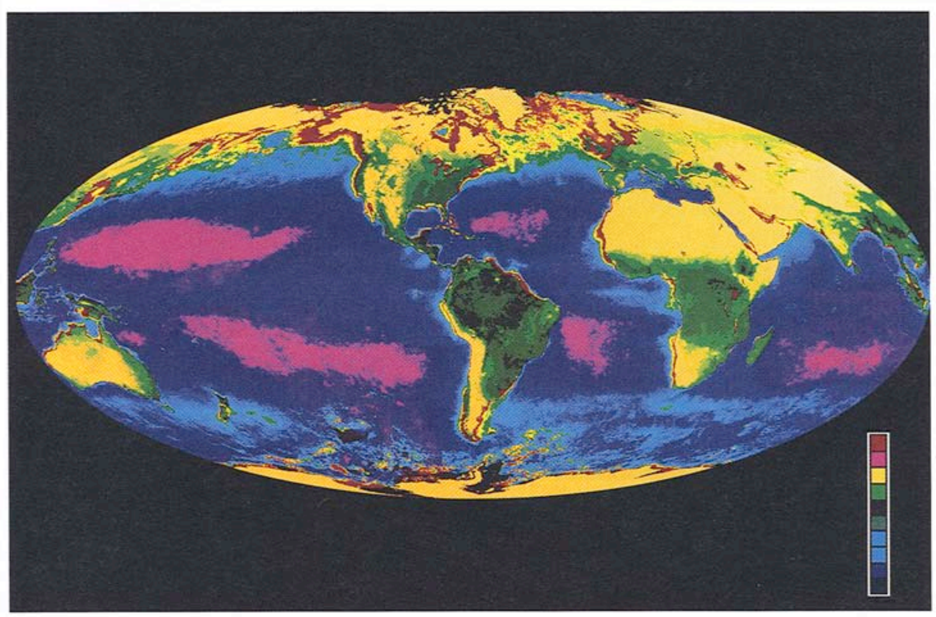
Illustration below shows how spectrum can give information about characteristics of a planet (what planet do you think this is?)



Detecting “biosignatures” from a planet’s spectrum.
Notice ozone (photosynthesis) and methane (bacteria).



If we could travel to an Earth-like planet orbiting another star:



The Earth's Biosphere This computer-generated picture shows the distribution of plants over the Earth's surface. Ocean colors in the order of the rainbow correspond to phytoplankton concentrations, with red and orange for high productivity to blue and purple for low. Land colors designate vegetation: dark green for the rain forests, light green and gold for savannas and farmland, and yellow for the deserts. (NASA)