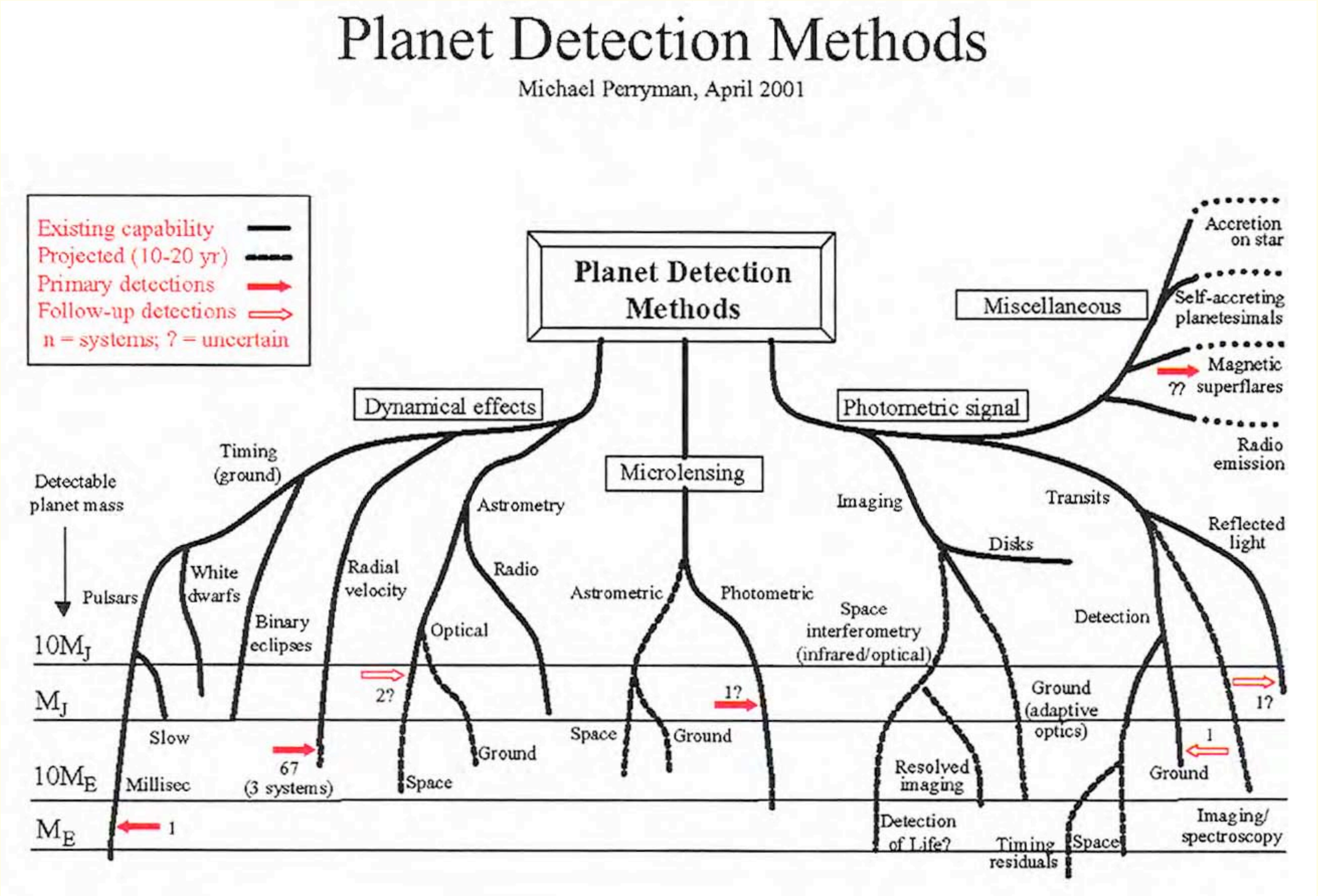
Hunting for Extrasolar Planets: Methods and Results

(Sec. 10.3 in your textbook)

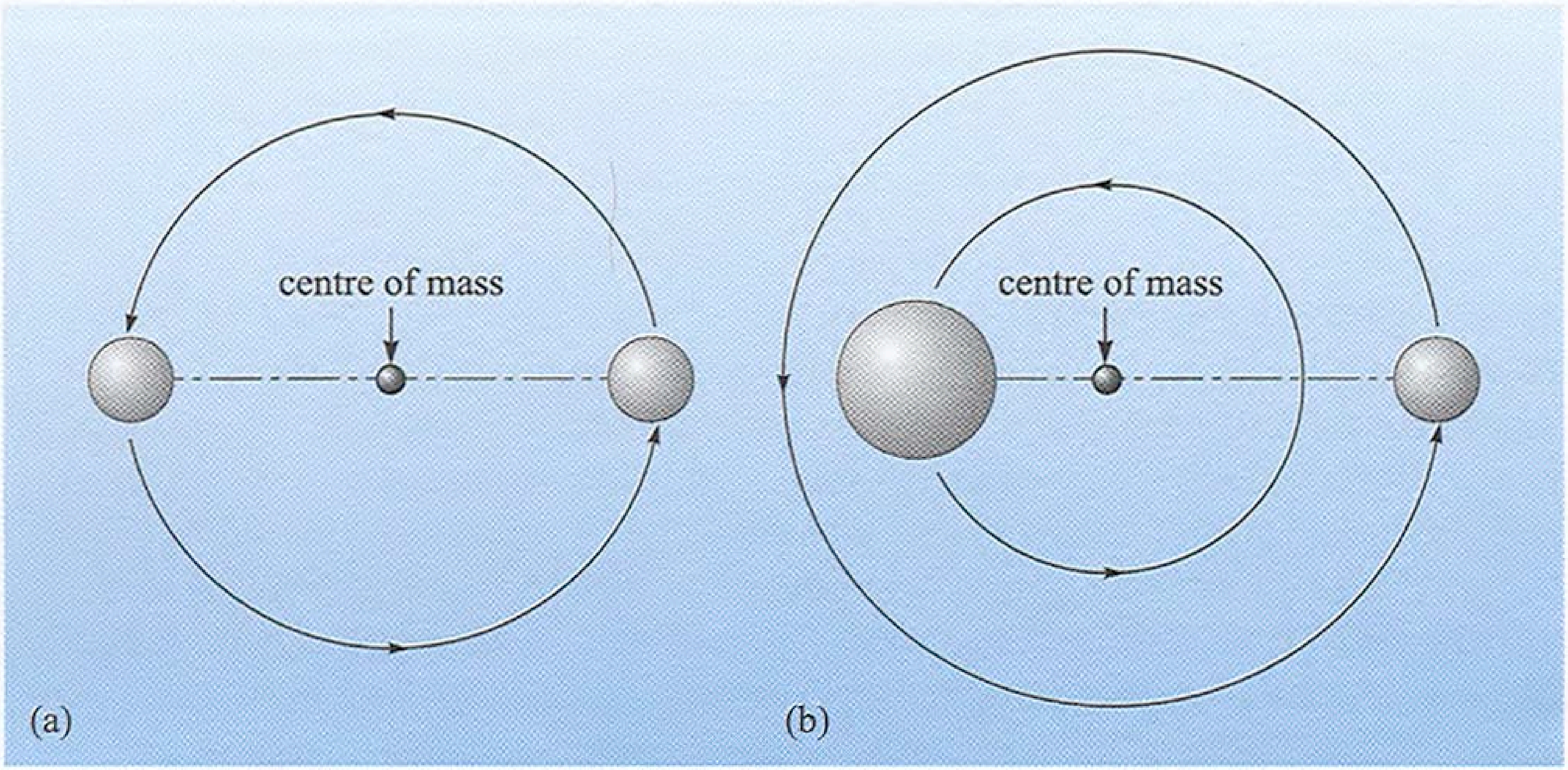
How to define a "planet"?? By mass, but what mass? By how it formed, but how would we know how something formed?

	STARS	BROWN DWARFS	GIANT PLANETS	TERRESTRIAL-LIKE PLANETS
	O star … Sun… M star	(BD limit)	Jupiter	Earth
Mass (solar units)	100$M_\odot$ … 1 …	0.08$M_\odot$ … ?	… 0.001	… 0.000003$M_\odot$
Mass (Jupiter units)	1000M_J …	80M_J … ?	… 1	… 0.003M_J
Surface temperature	**50,000K … 6,000K…3,000K …**	**1,000K**	**… ~500K**	
Color	blue → yellow → red →	…	**infrared**	
	formed from cloud collapse		formed from protostellar disk	
Heat source	nuclear fusion	gravitational heating, fading		light from parent star, internal radioactivity
	gaseous			solid surface

There are a large number of techniques for detecting extasolar planets, each of which is sensitive to planets and parent stars with different properties. We will discuss only the most promising/successful methods.

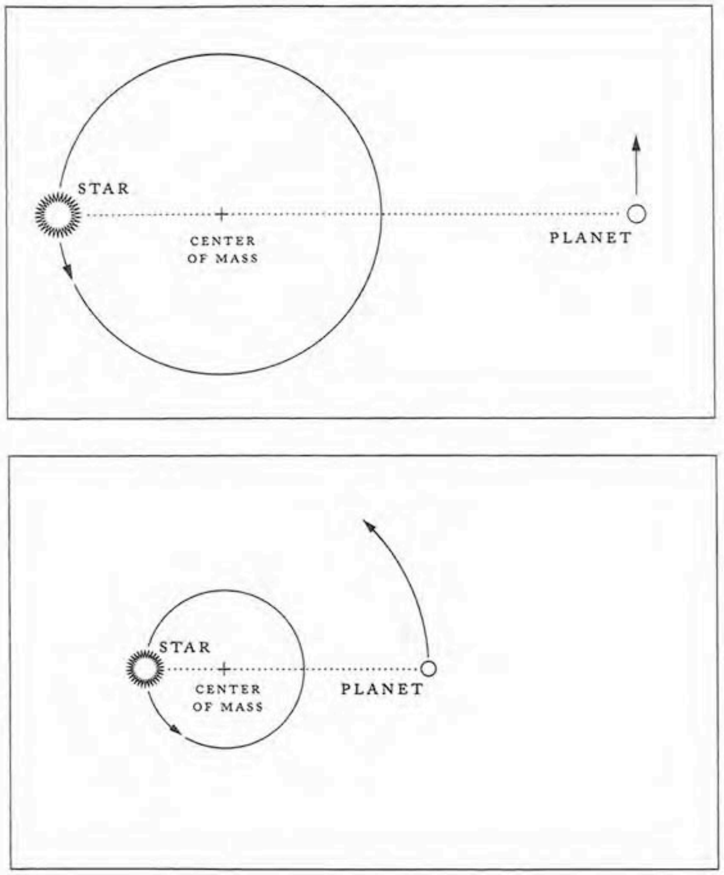


Two objects orbit their center of mass, or "barycenter." The barycenter is closer to the more massive object (star) than the less massive object (planet). A star is so much more massive than a planet that the barycenter is very close, or even inside, the star

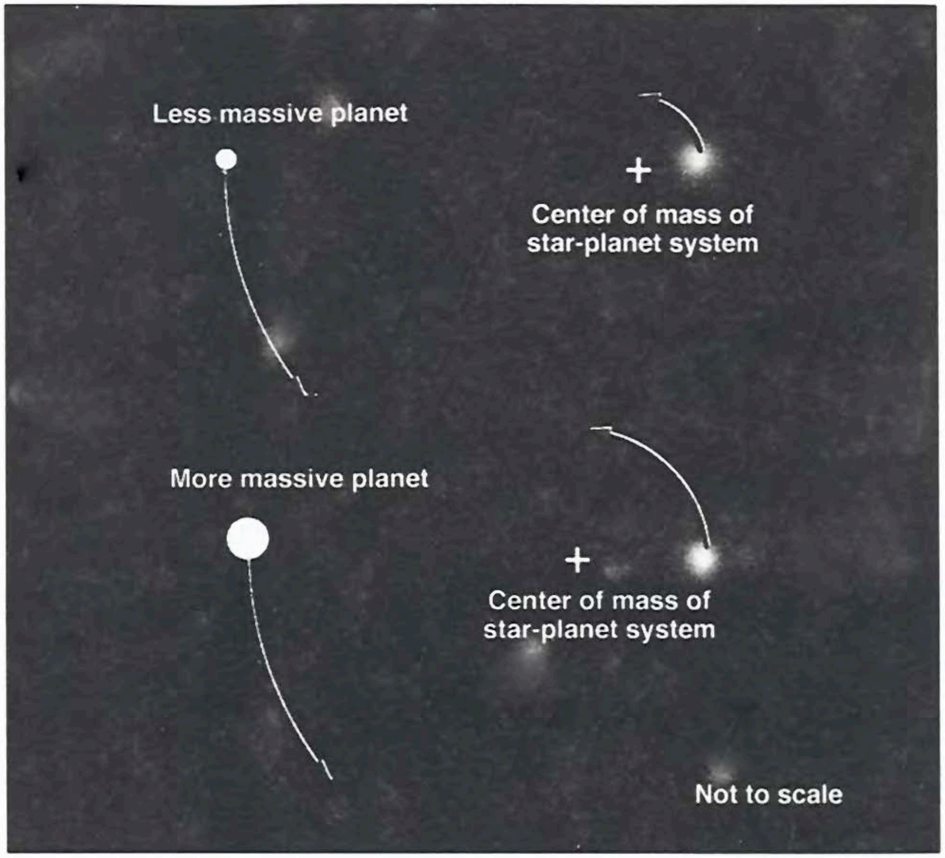


The orbits of a two-body system, showing the centre of mass in each case, for (a) two equal masses; (b) one mass greater than the other.

Effect of planetary distance(right) and mass (left) on the "wobble" of the parent star

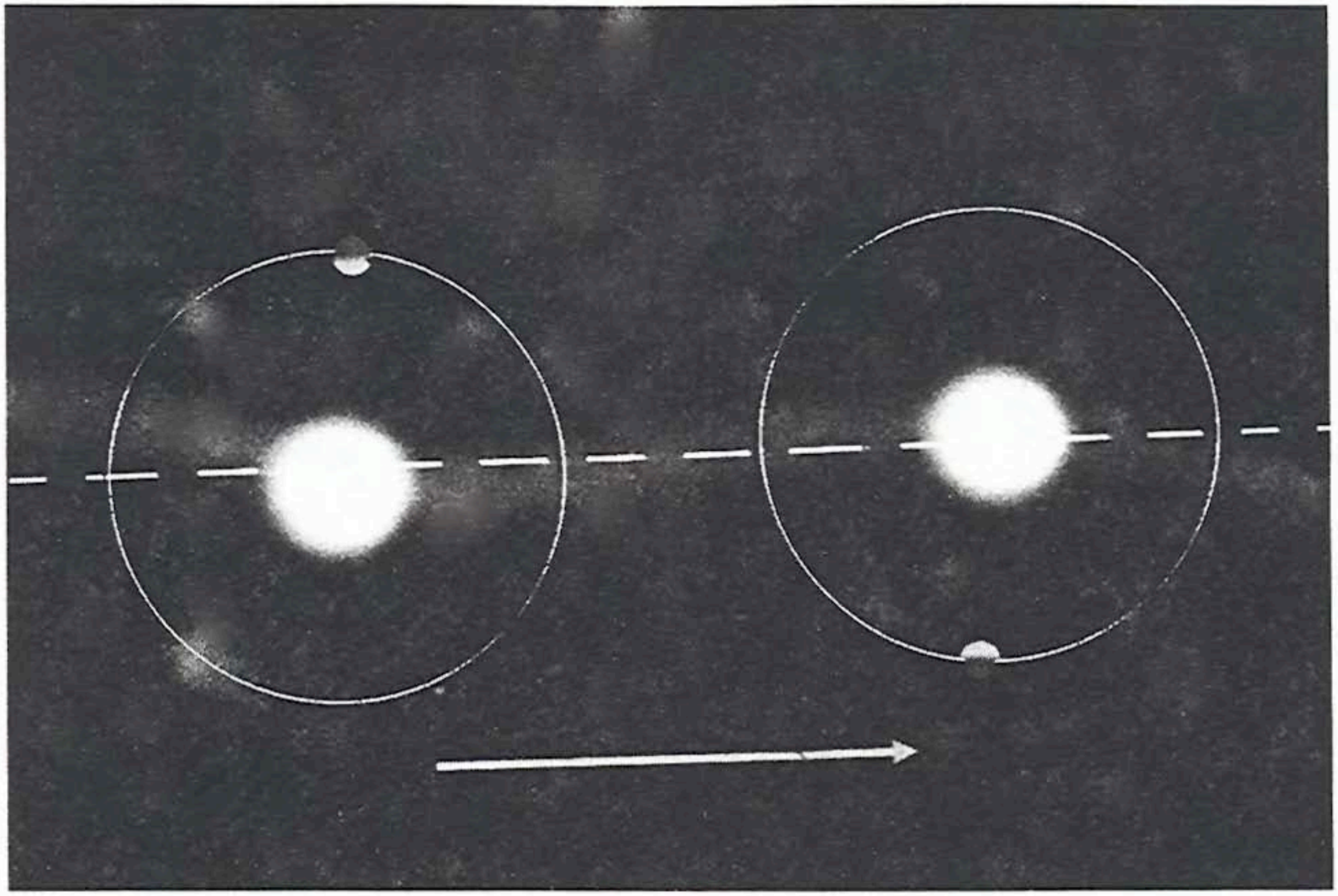


If a planet lies far from its star (top), the star will execute a large wobble around the center of mass, a wobble that astrometrists have a chance to detect; but the star will move only slowly, so Doppler observers, who measure stellar speeds, will fail. On the other hand, a star with a close-in planet (bottom) orbits around the center of mass fast, because the planet's period is short. This gives Doppler observers the chance to detect the wobble. But because the wobble is small, astrometrists, who measure the wobble's size, are out of luck.



A planet orbiting at a specific average distance from its star will produce changes in the star's velocity that are greater for planets with larger masses. This fact allows astronomers to deduce the mass of the planet once they estimate the mass of the star and have derived the average distance at which the planet orbits (from their knowledge of the orbital period and the star's mass).

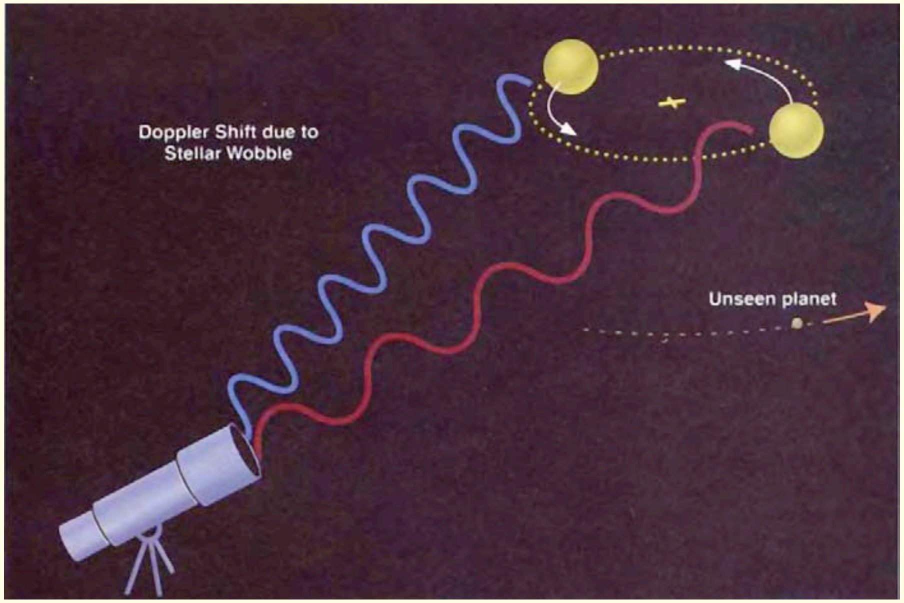
Astrometric method: Must detect very small "wavy" motion of the star along its path (milli- or even micro- arcseconds) in the sky. Extremely difficult, and most sensitive to planets far from star, so takes many years. Future space mission SIM detect thousands of planets using this method (see pp. 255-256 in textbook).

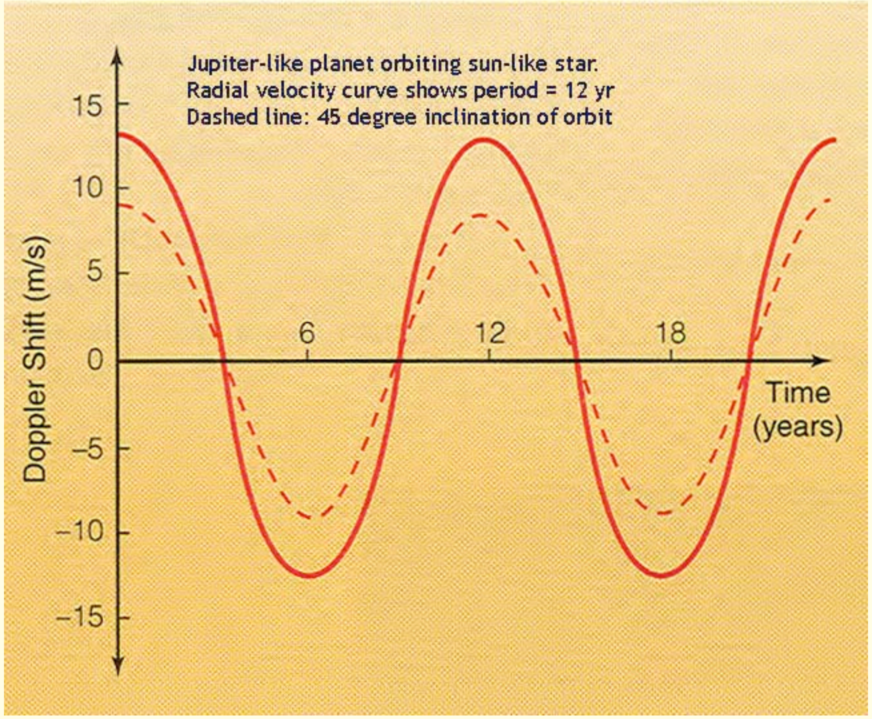


If we can measure a star's apparent motion through space with sufficient accuracy, we can hope to observe the deviations from straight-line motion that the gravitational force from a planet or planets orbiting the star will produce.

Radial velocity method:
Search for periodic radial velocity variation in parent star.

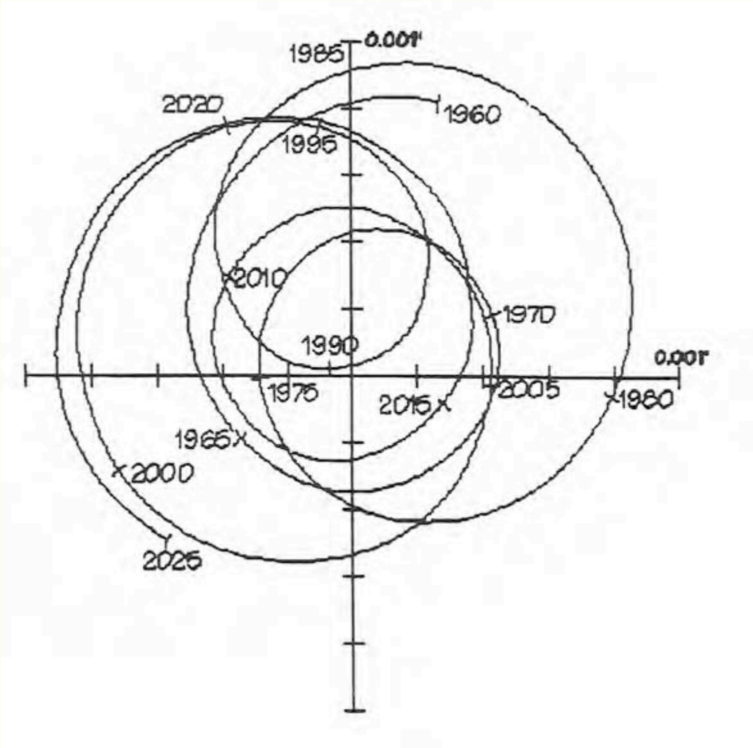
Periodic Doppler effect due to orbital motion → Resulting ***radial velocity curve***



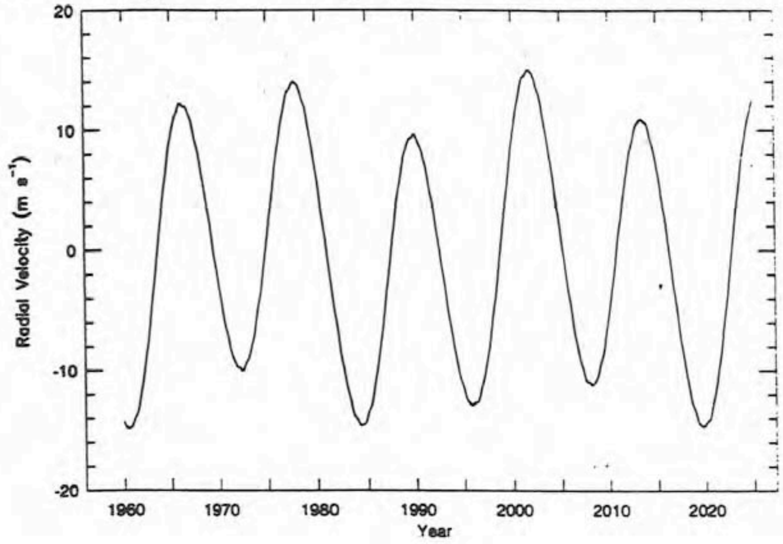


See Figs. 10.6, 10.7, 10.8 in textbook

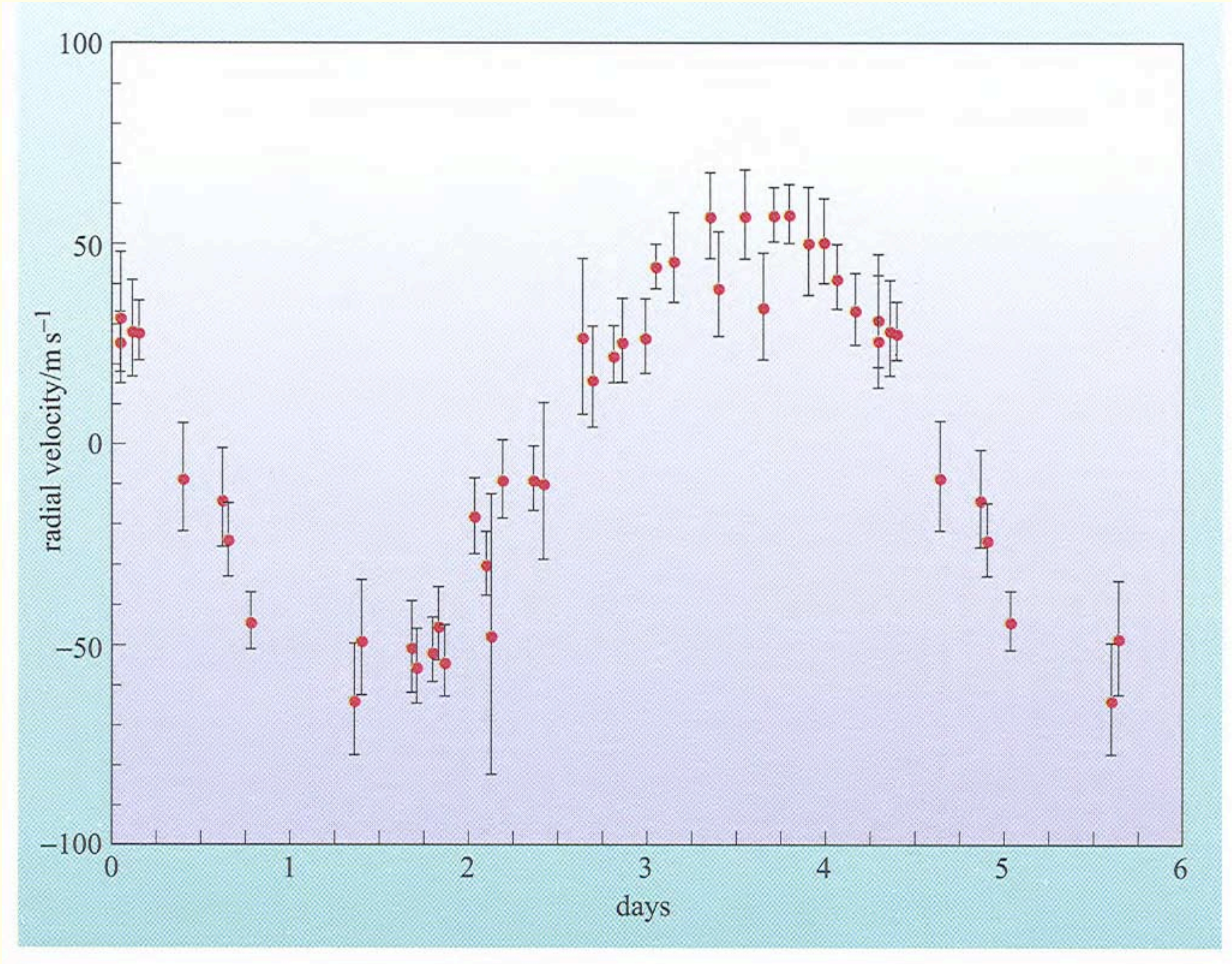
Sun's motion about the solar system barycenter due to all the planets, and resulting radial velocity curve: Small (hard to measure) effect and should take years!



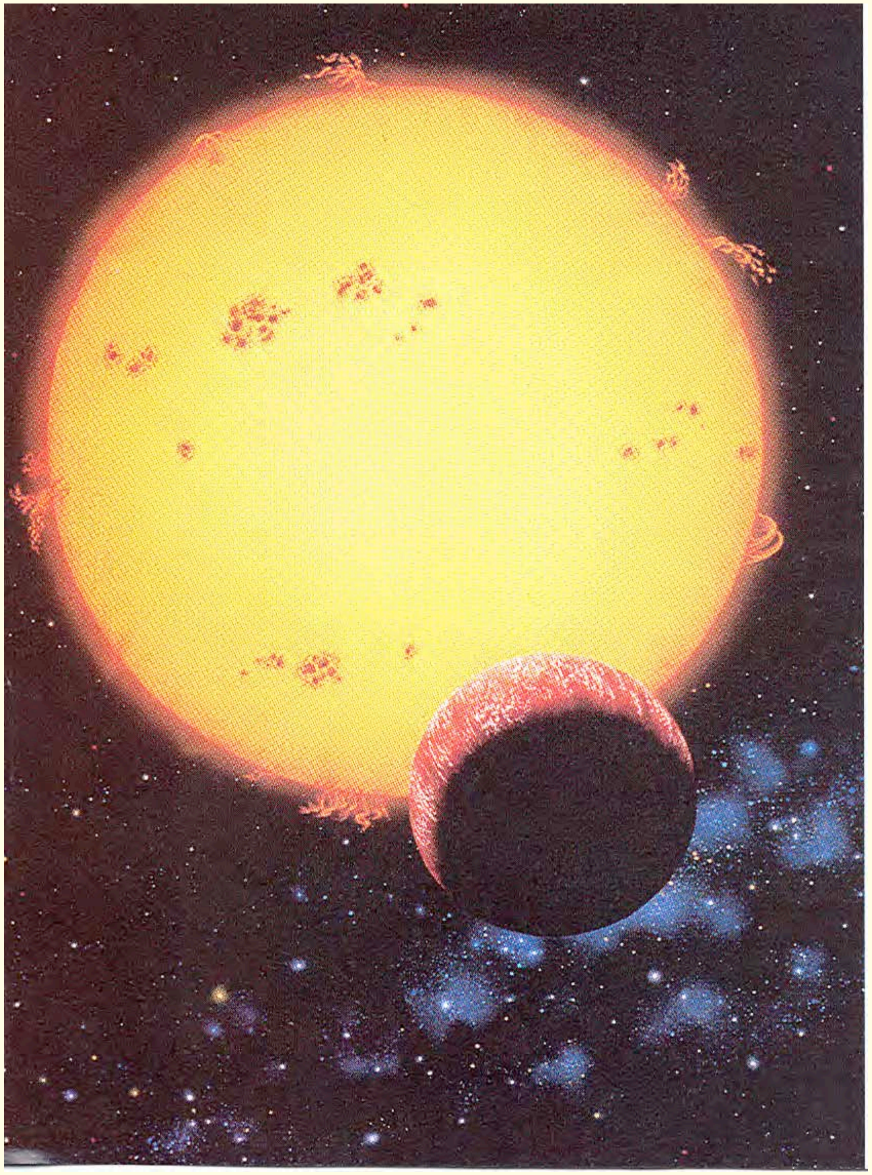
The radial velocity of the Sun with respect to the Solar System barycenter at the same time:



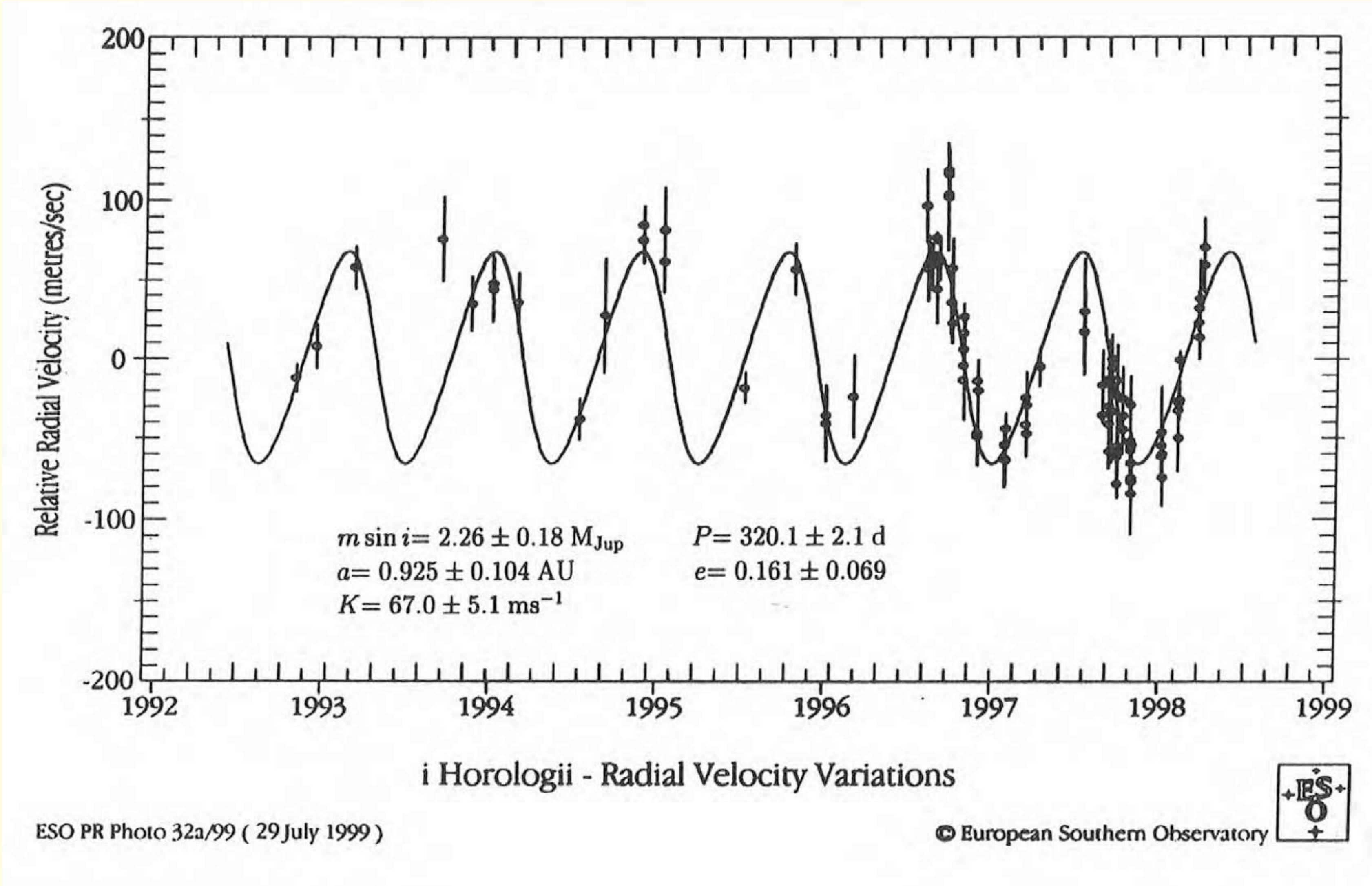
Big surprise in 1995: Radial velocity curve of star 51 Pegasi shows *large* radial velocity amplitude and orbital period of *days*, not years! Must be giant planet *very* close to its parent star.



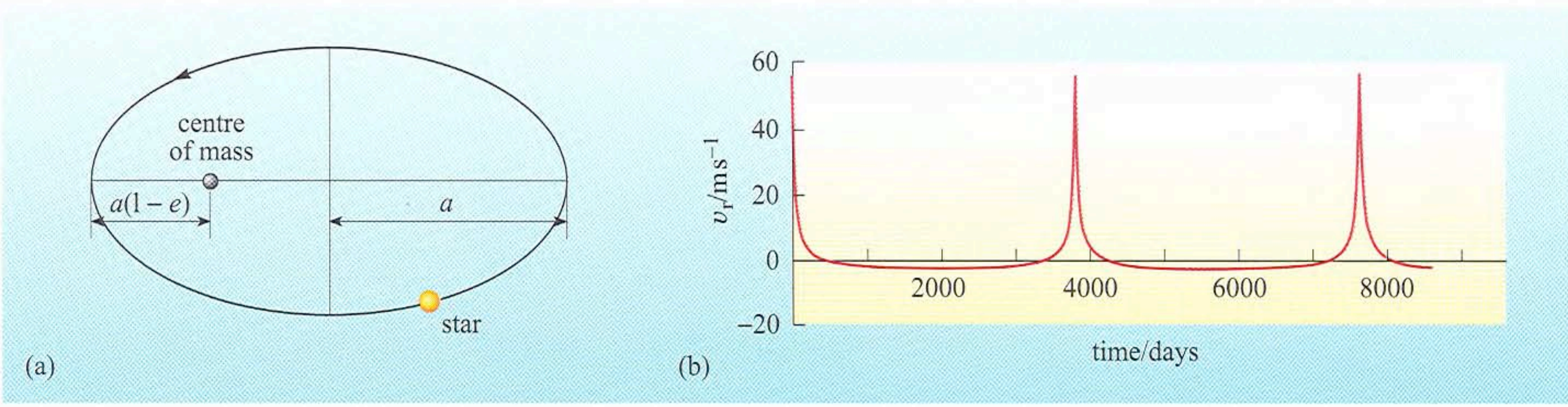
Many of these close-in “hot Jupiters” were subsequently discovered--this is just the kind of system that the radial velocity method works best for.. But how could a Jupiter-like planet be formed so near to its parent star?



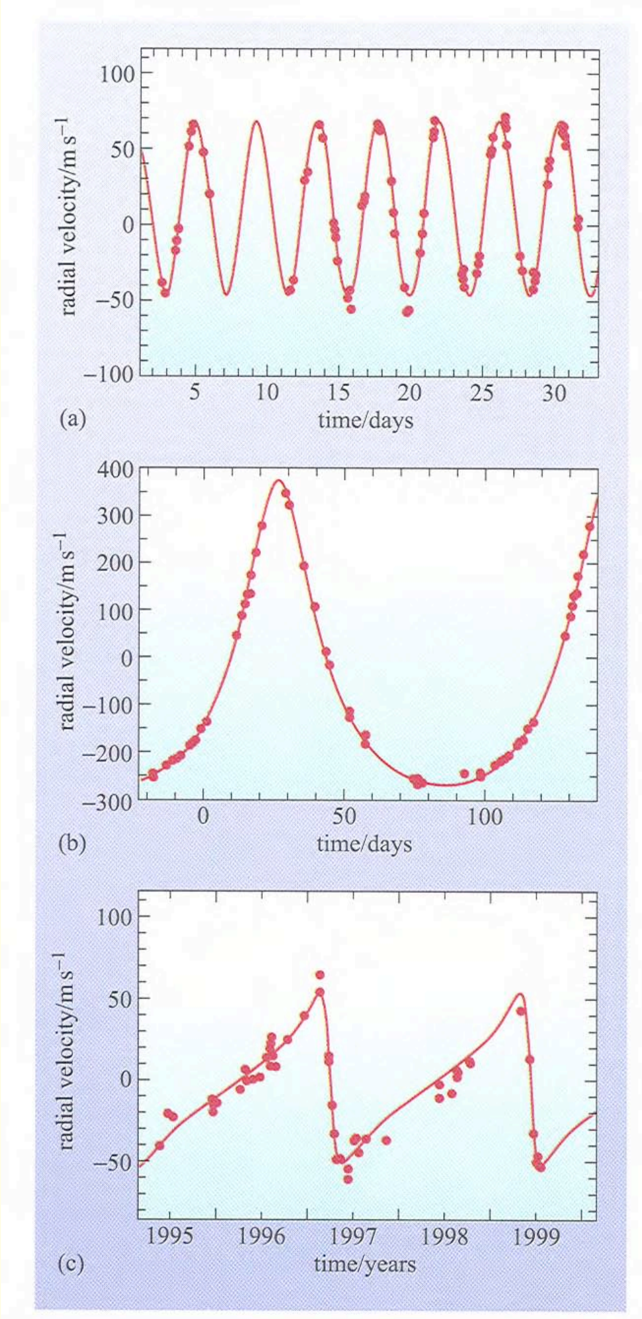
After monitoring for years, more giant planets at larger distances from their parent star were discovered. Notice the pattern of confirmation of the existence of the planet--this is typical.



The radial velocity method allow us to measure the eccentricity of the orbit, because of variations in orbital velocity around the elliptical orbit (Kepler's laws).



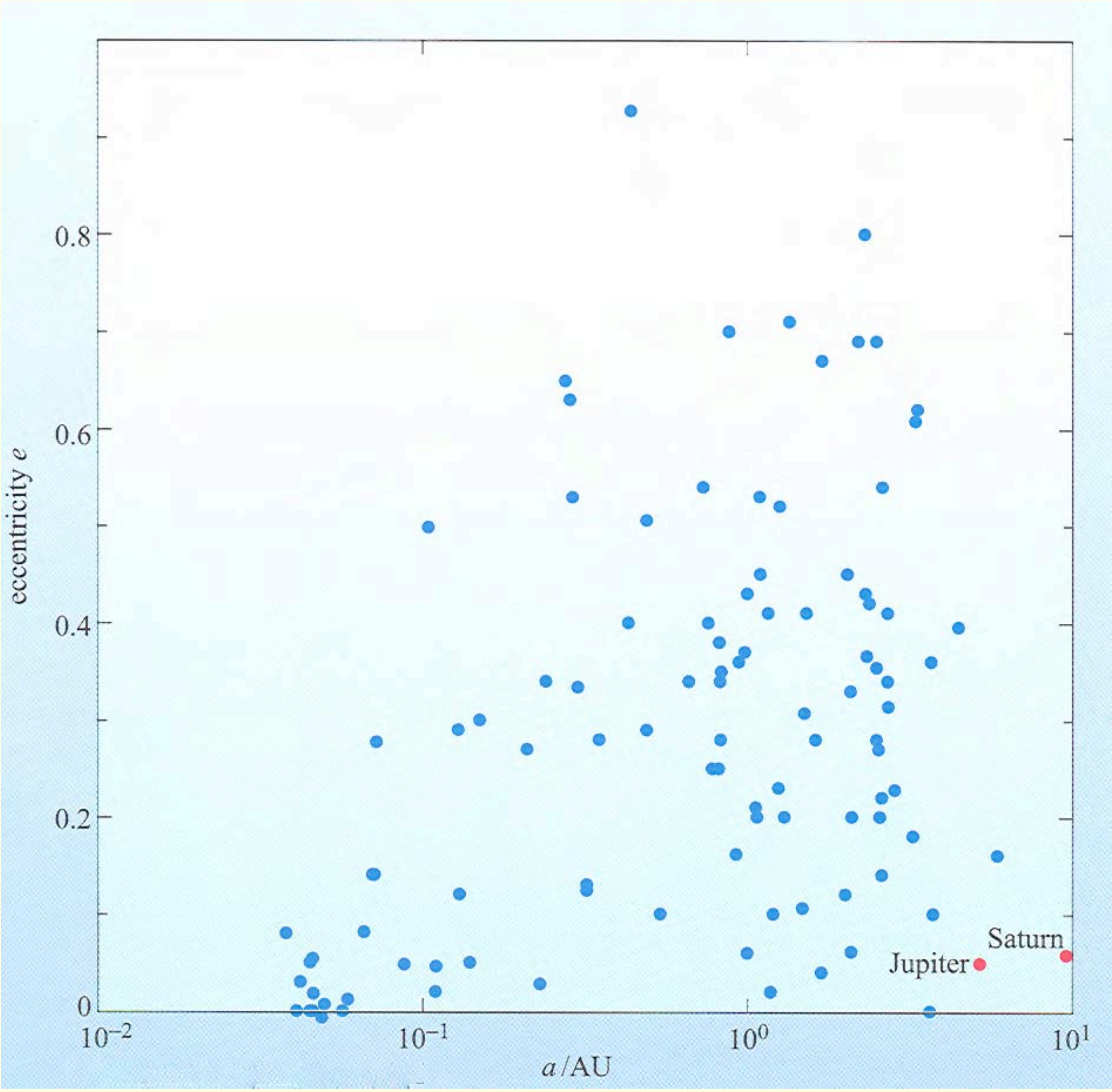
(a) An elliptical orbit. The semimajor axis a is half the widest distance across the ellipse, and the star is located at $a(1 - e)$ along the major axis, where e is the eccentricity. For $e = 0$, the orbit is circular and a equals the radius of the orbit. (b) The radial velocity profile for an elliptical orbit having an inclination of 90° and oriented so that its major axis lies in the plane of the sky. The large, narrow, positive peaks correspond to the times when orbital speeds are greatest (at closest approach).

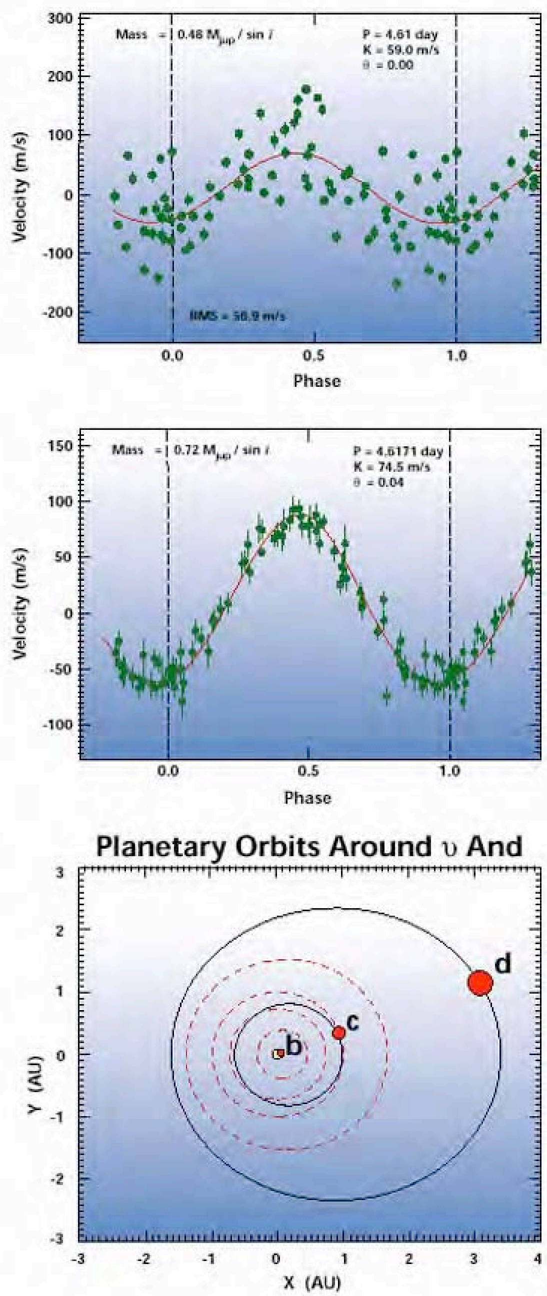


Depending on eccentricity of the orbit and viewing angle, can get different forms of the radial velocity curve. The surprising thing is that there are *any* giant planets with such eccentric orbits. Gravitational forces should "circularize" orbits over time.

This could be bad news for the survival of Earth-like planets.

Eccentricity vs. semimajor axis (distance from parent star) for many of the known giant exoplanets (also see textbook Fig. 10.14). Large number of very close-in "hot Jupiters" with large eccentricities! (Notice Earth is at 1 AU, Mercury at 0.4 AU from Sun.)





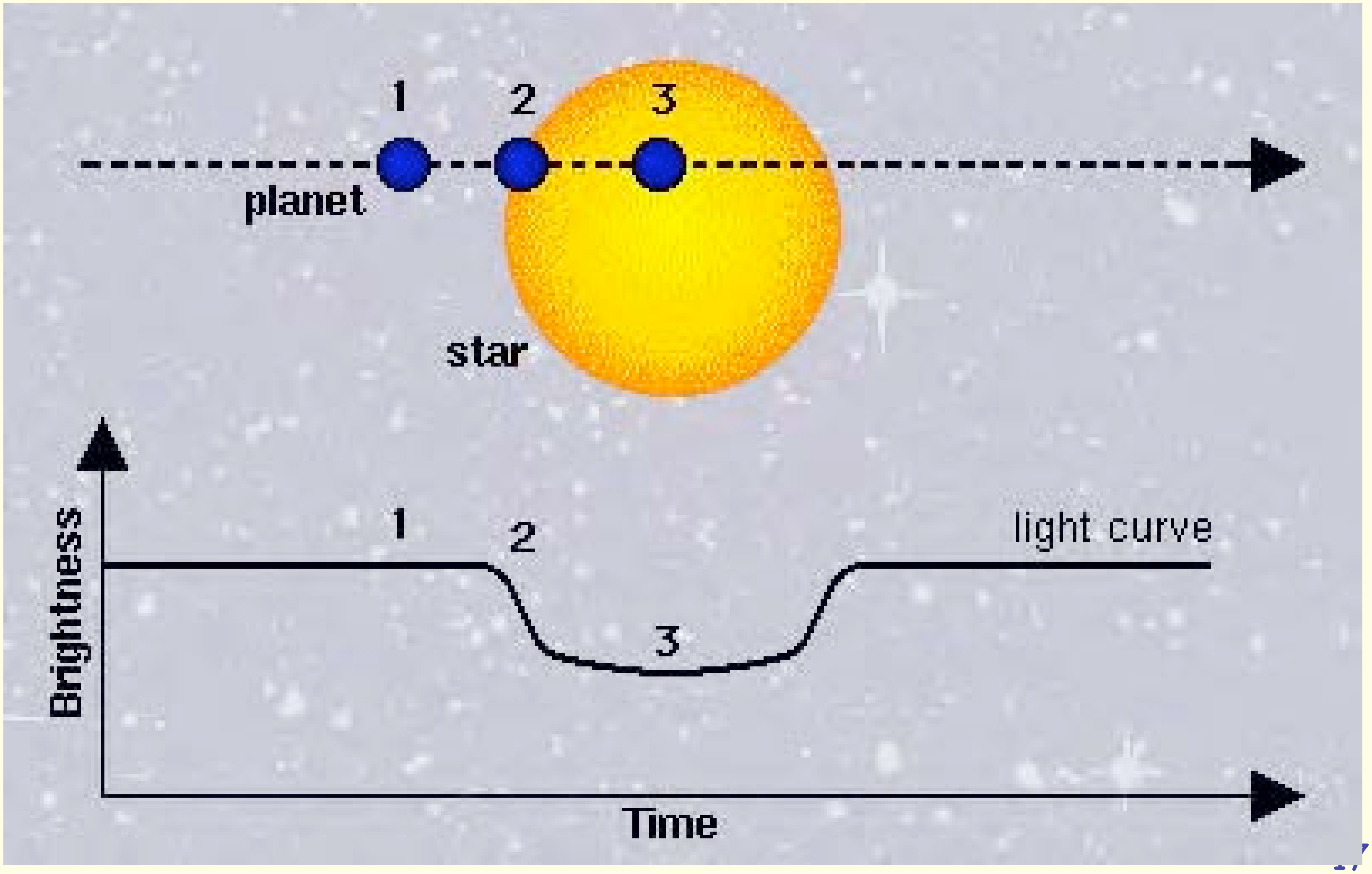
Radial velocity measurements have been used to infer the presence of multiple planets orbiting Upsilon Andromedae. The fit to the data for a single planet is relatively poor (top), while the fit for each planet is improved when the presence of three planets is taken into account (middle). Planets B, 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).

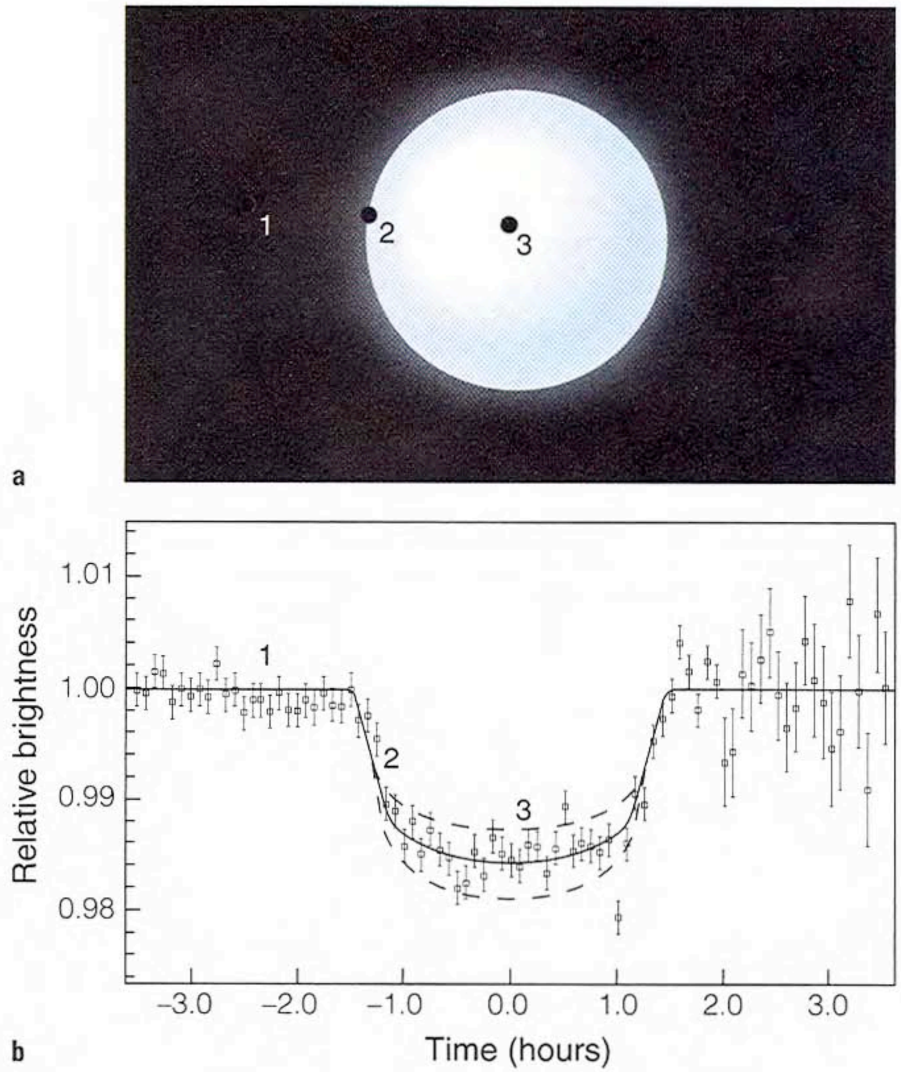
A landmark in extrasolar planet discovery: A star with a multiple (giant) planets. So there might be other "solar systems."

Understand the advantages and disadvantages of the astrometric vs. the radial velocity method. Read about the potential of the future SIM space mission for planet detection in your textbook.

	Astrometry	Doppler
Easiest planetary mass to detect?	Large	Large
Easiest planetary distance from star?	Large	Small
Easiest orbital period of planet?	Long	Short
Best distance of star from Earth?	Nearby	Irrelevant
Can mass of planet be measured?	Yes	No; only a minimum

A photometric method: Transits. This is the most active area of planet searching today because 1. It does *not* require a large telescope! 2. Chances of finding a planet-star system nearly edge-on is small, so need lots of observations; 3. Big payoff: you can learn about a stars diameter *and* mass, and so get density. Also: can observe planet's spectrum!

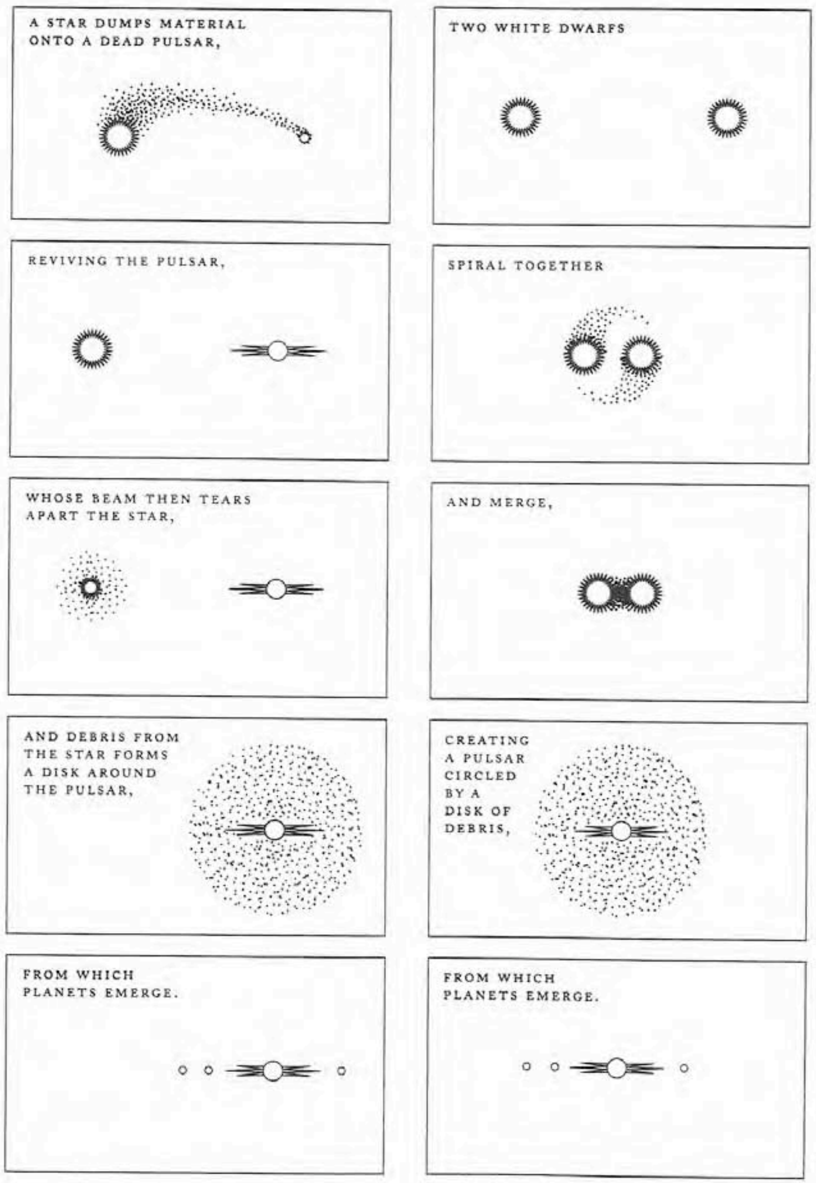




Careful measurements of the brightness of the star called HD209548 revealed that an orbiting planet passes directly in front of it as seen from Earth, which means that the planet's orbit must be edge-on as seen from Earth. (**a**) Artist's conception of the planet as it passes directly in front of its star as seen from Earth. (**b**) These data show the 1.7% drop in the star's brightness that proved the planet is passing in front of the star as seen from Earth.

In practice this method is very difficult, because you have to monitor a huge number of stars (most of which won't have suitable planets for transit discovery) *and* the effect you're looking for is extremely small--about 1% for a giant planet.

(This is Fig. 10.11 from your textbook.)

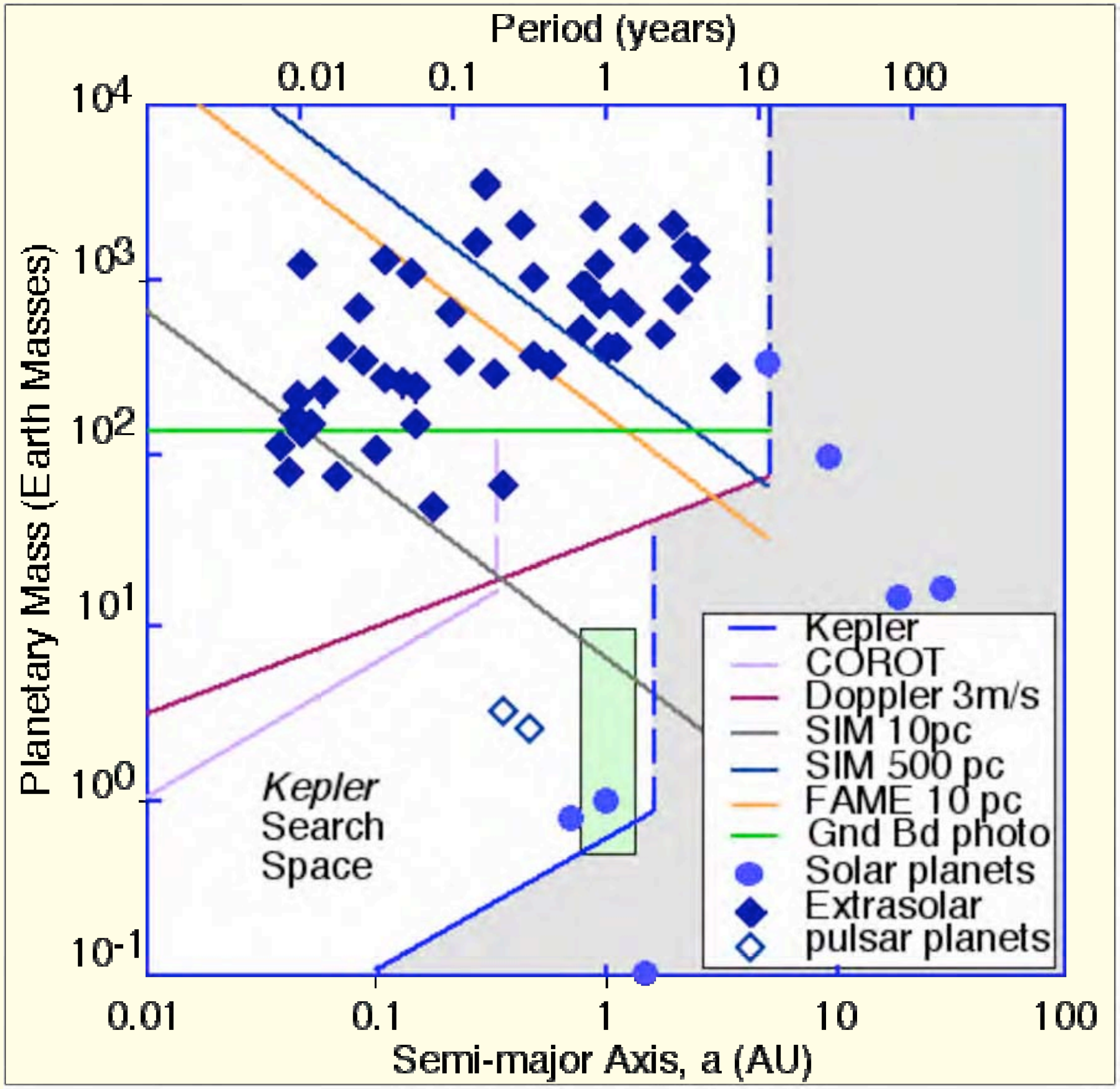


Pulsar planet production. Pulsar planets may arise when a reborn pulsar tears apart its companion star (left) or when two white dwarfs merge (right).

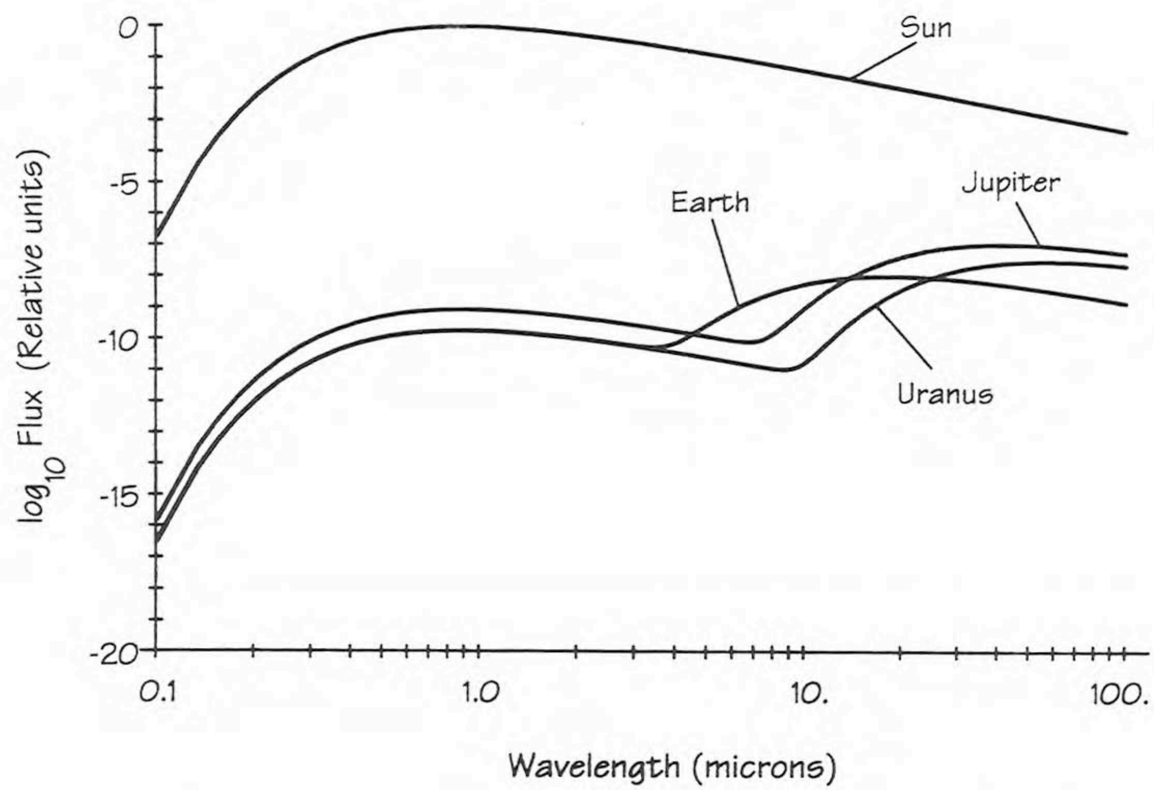
Proposed model for the origin of the "pulsar planets."

Make sure you understand the method by which they were detected (discussed in class).

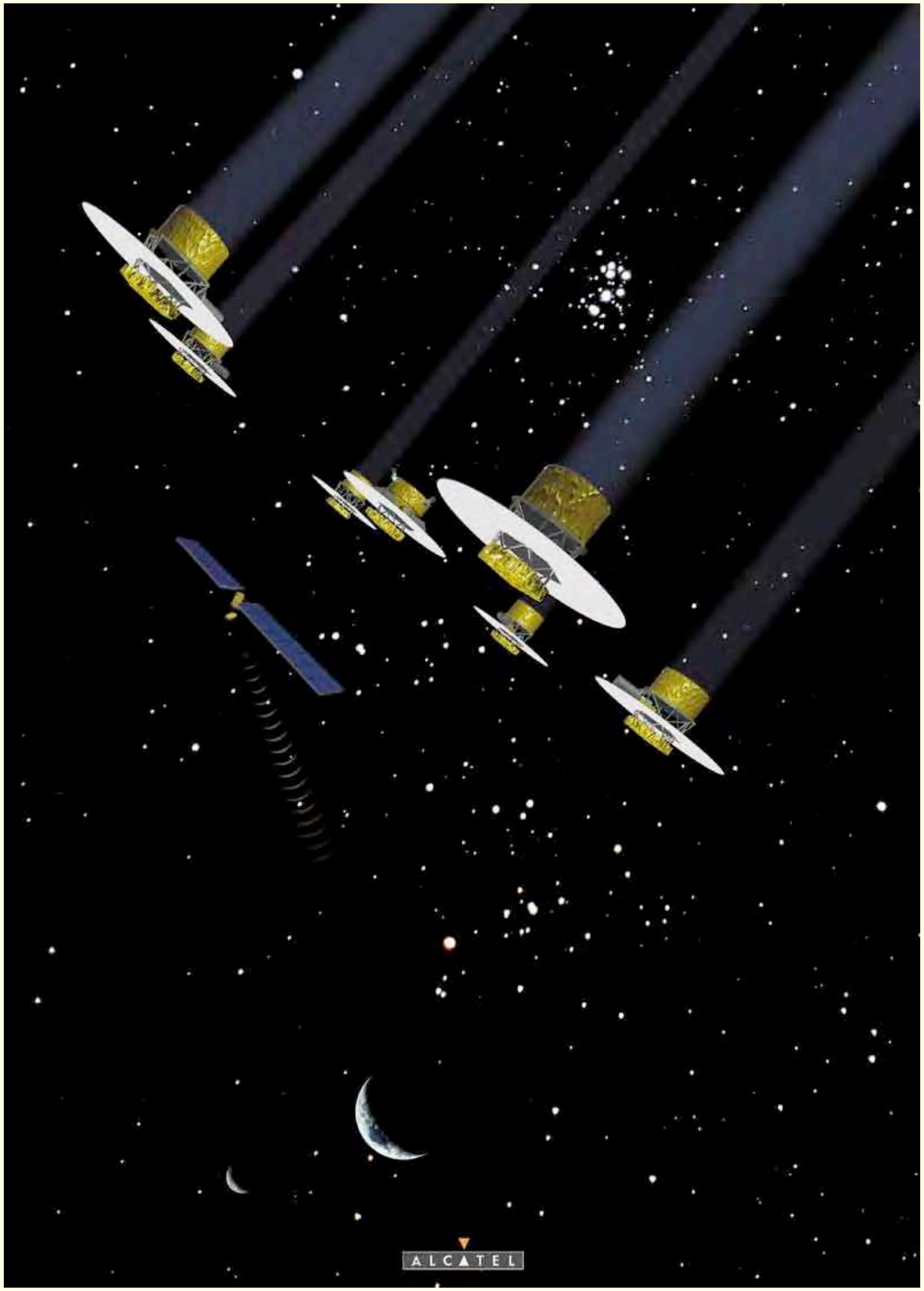
Detection limits for various planet detection techniques and future missions, along with positions of many known extrasolar giant planets and planets in our solar system. If you can explain many of the features of this plot, and describe the different mehtods, you will do well on this part of the exam.



This is a major reason why ***direct detection*** (seeing the planet itself) is too difficult for now, except perhaps for giant planets: The starlight swamps the emission from the planet. We will return to direct detection of Earth-like planets after discussing other methods.



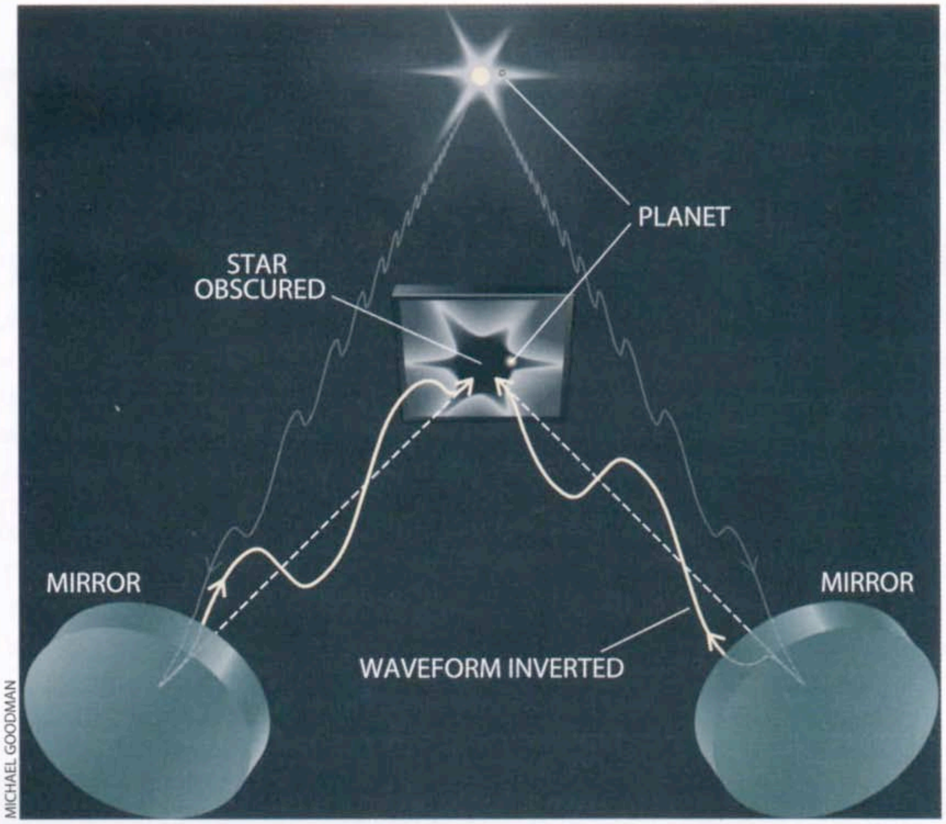
The spectral energy distributions of the Sun, Jupiter, Earth, and Uranus as they would appear at 5 pc, averaged over a 10% spectral bandpass. Note the decreased ratio of solar to planetary flux in the thermal infrared, compared to visible wavelengths.



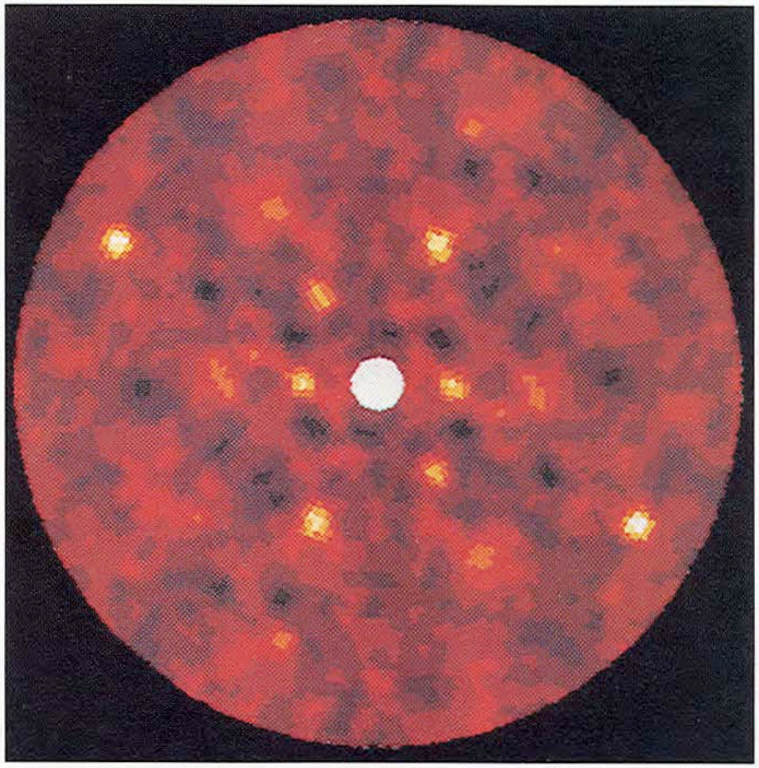
Direct detection of terrestrial-like planets. Recall that major problems are seeing the reflected light or infrared emission from the planet in the glare of the star, and resolution: the angular separation of the star-planet will be extremely small (tiny fraction of arcsecond). So need a very large telescope in space: Terrestrial Planet Finder/Darwin (artist conception Shown to left)

How will TPF block the starlight? What wavelength region(s) will be used and why?

Nulling interferometer (left) and simulated detection of terrestrial-mass planets by TPF (right). Interferometer makes double images of each planet on opposite sides. This tells us the planets are there, but what we *really* want is the **spectra** of Earth-like exoplanets.



CANCELING STARLIGHT enables astronomers to see dim planets typically obscured by stellar radiance. Two telescopes focused on the same star (*top*) can cancel out much of its light: one telescope inverts the light—making peaks into troughs and vice versa (*right*). When the inverted light is combined with the noninverted starlight from the second telescope (*left*), the light waves interfere with one another, and the image of the star then vanishes (*center*).



A computer simulation of Earth-like planets around another star, as imaged by a set of telescopes in space. The instrument would work at 10 microns in the infrared, where the contrast of a planet with respect to the nearby star is favorable. Light from the separate telescopes is combined so as to efficiently blank out the central star; this process leads to two image of each planet, on opposite sides of the star. (SOURCE: Courtesy J. R. P. Angel and N. Woolf.)

Infrared spectra of Venus, Earth, and Mars (Fig. 10.16 in textbook). Notice features of ozone and water vapor for Earth

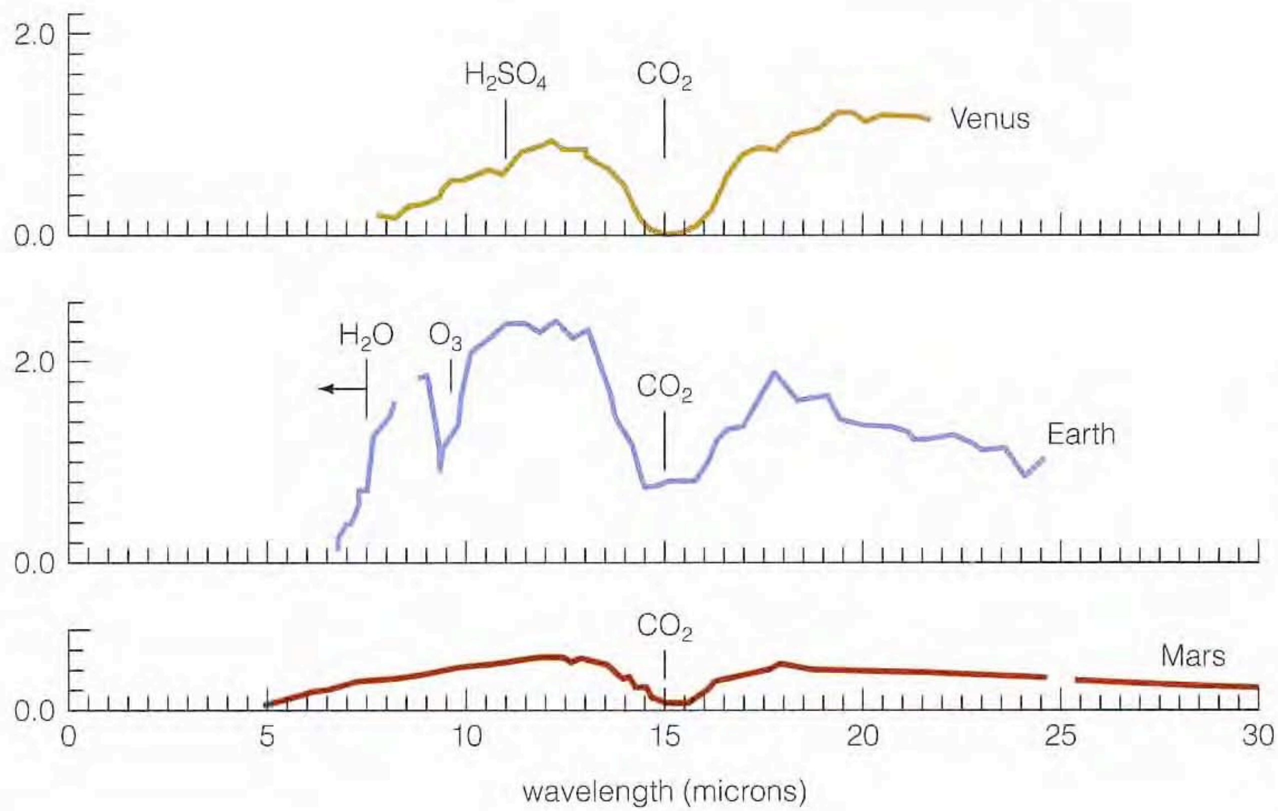
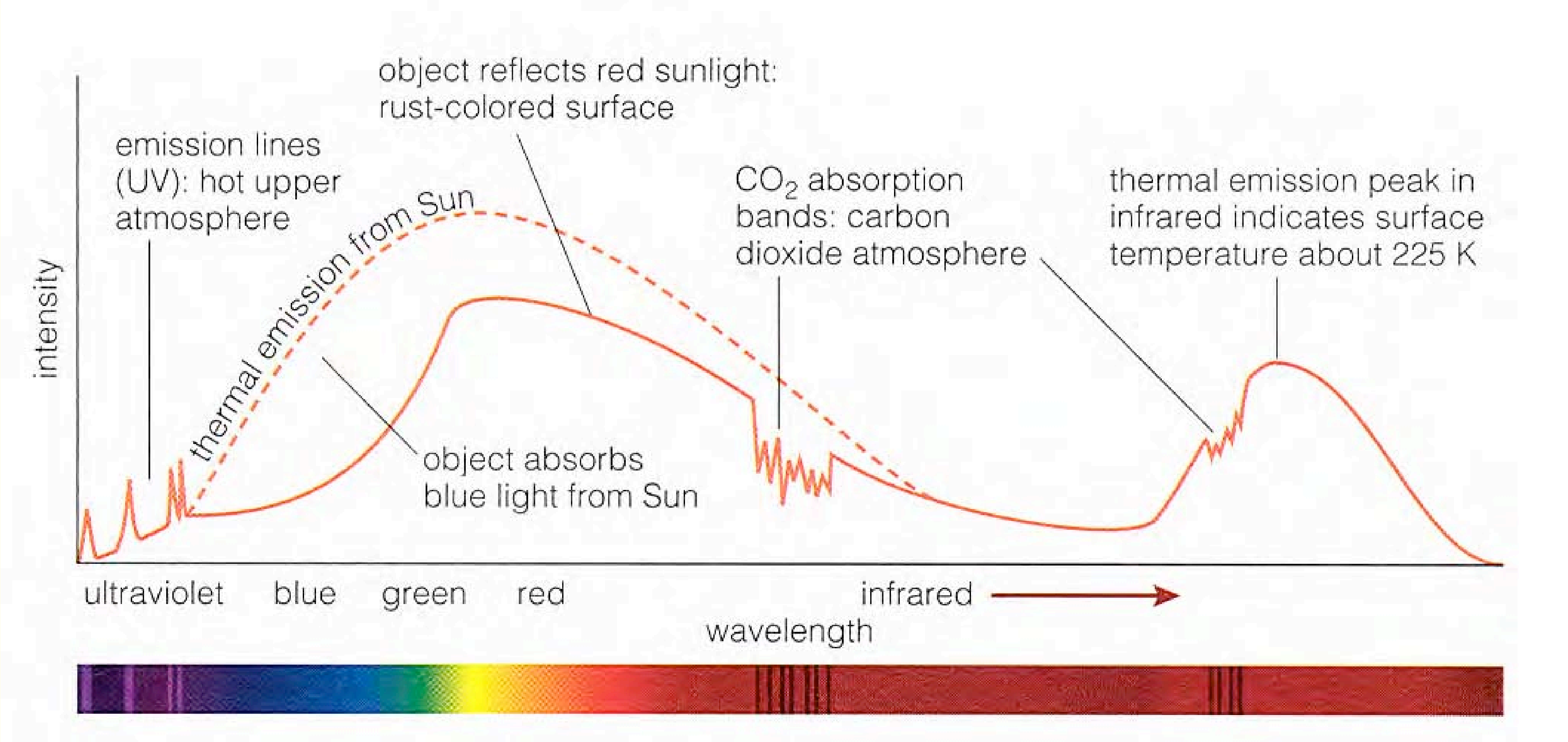
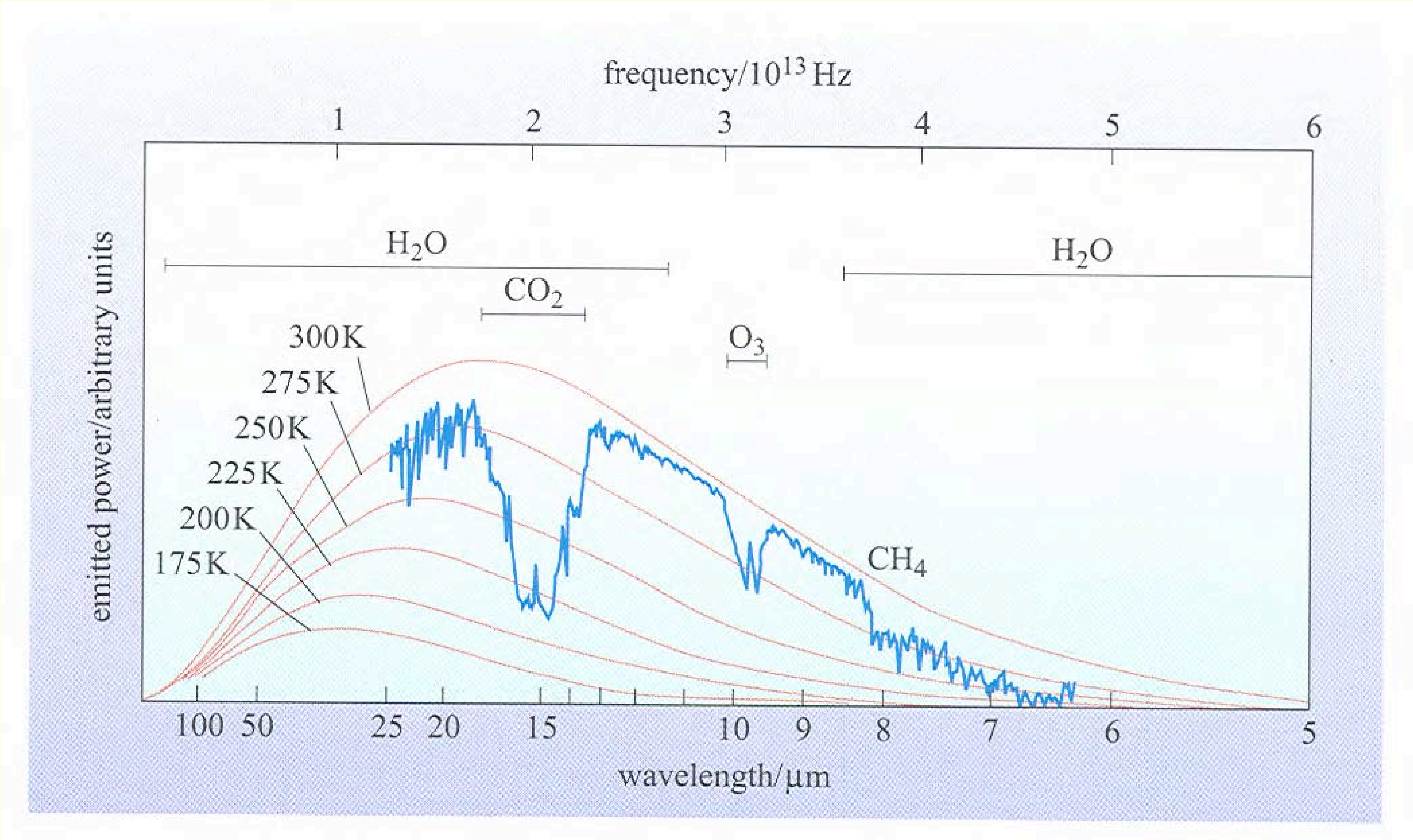


FIGURE 10.16 The infrared spectra of Venus, Earth, and Mars, as they might be seen from afar, showing absorption features that point to the presence of carbon dioxide (CO_2), ozone (O_3), and sulfuric acid (H_2SO_4) in their atmospheres. While carbon dioxide is present in all three spectra, only our own planet has appreciable oxygen (and hence ozone)—a product of photosynthesis. If we could make similar spectral analyses of distant planets, we might possibly detect atmospheric gases that would indicate life.

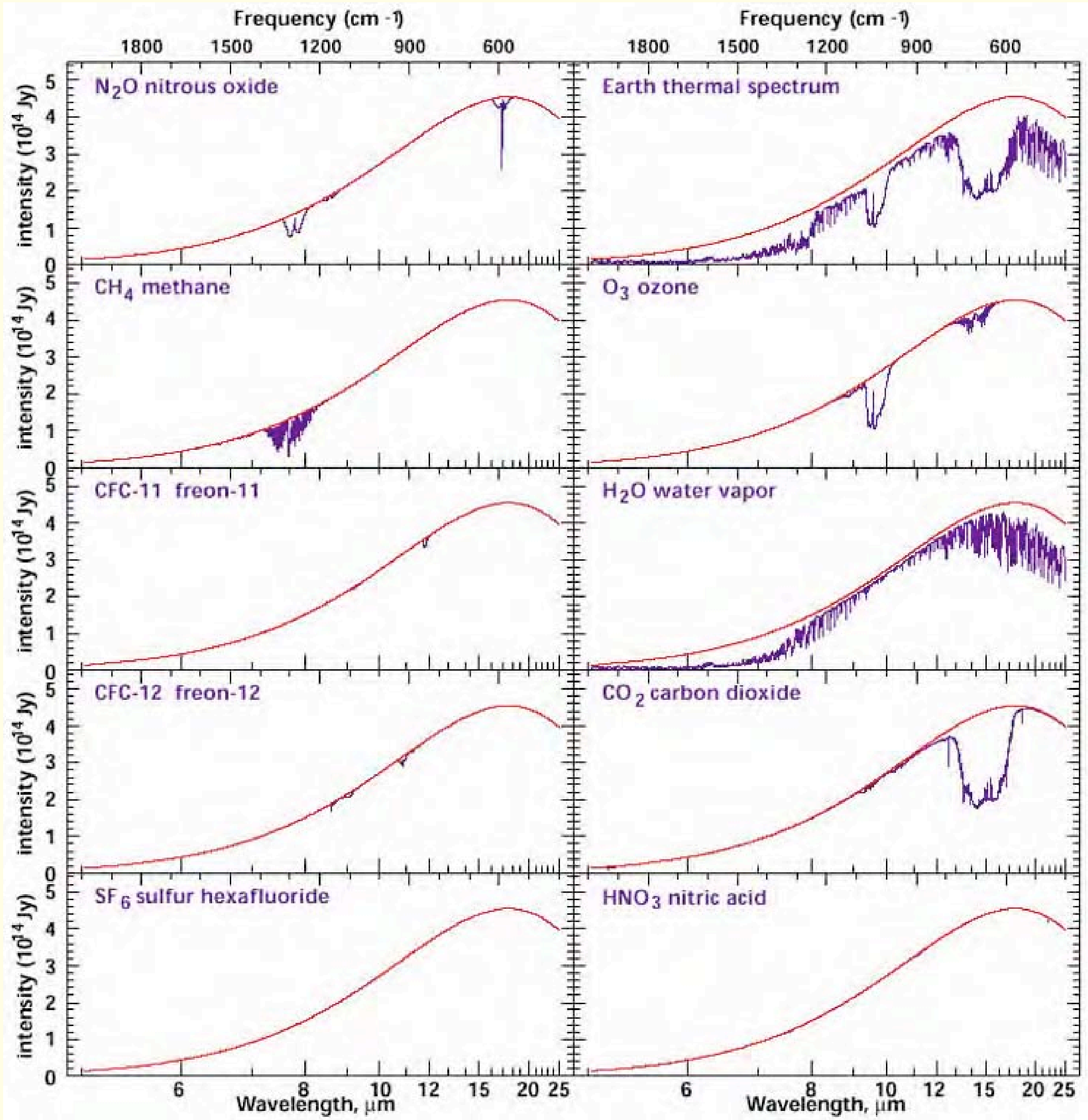
How the reflection (in visual) and emission (in infrared) spectrum tell you about the nature of the planet



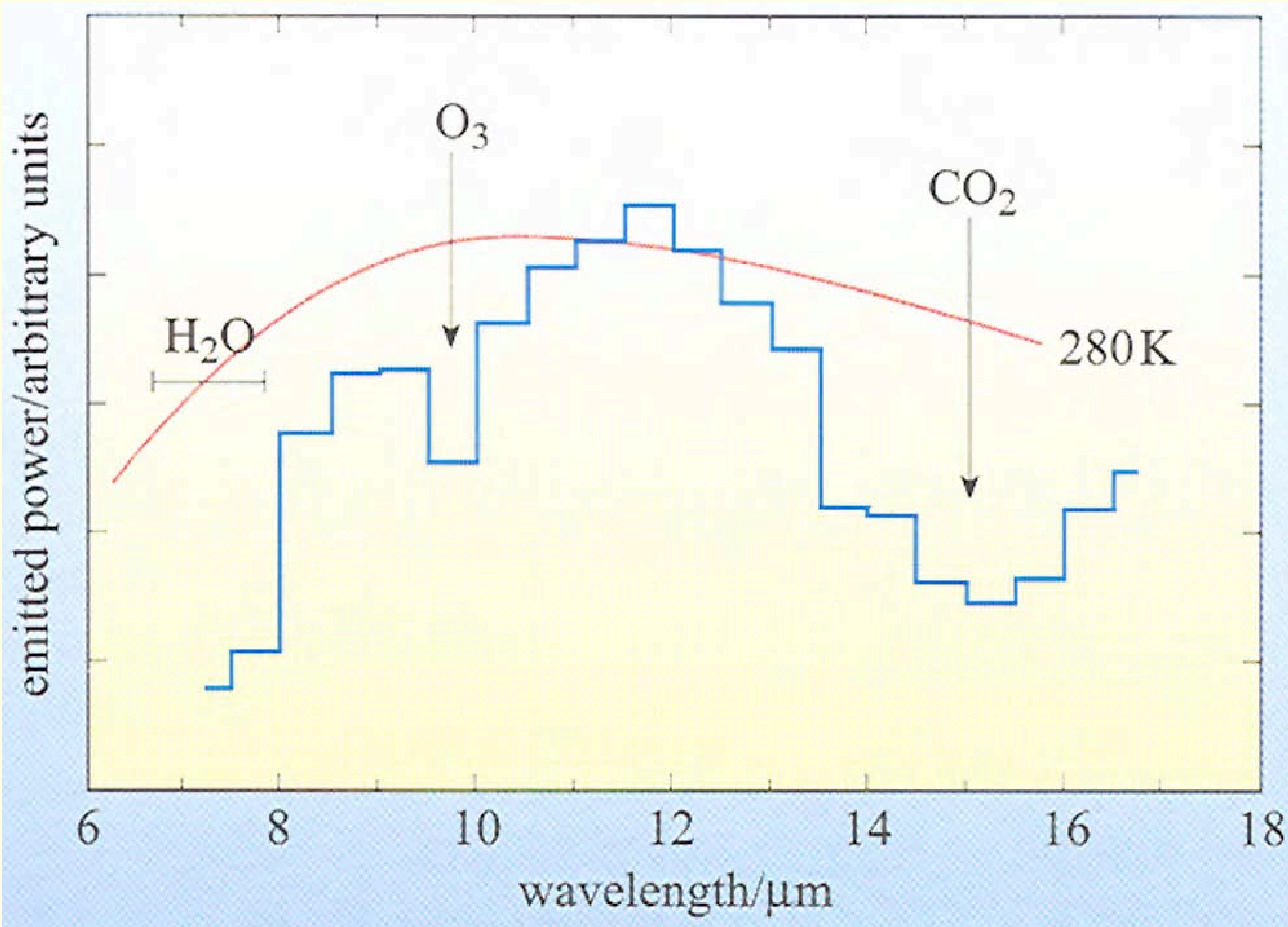
Infrared spectrum of the present Earth. Red curves are blackbodies of various temperatures. What are the potential signatures of life, or of habitability? (Note: wavelength increases to the left on this plot)



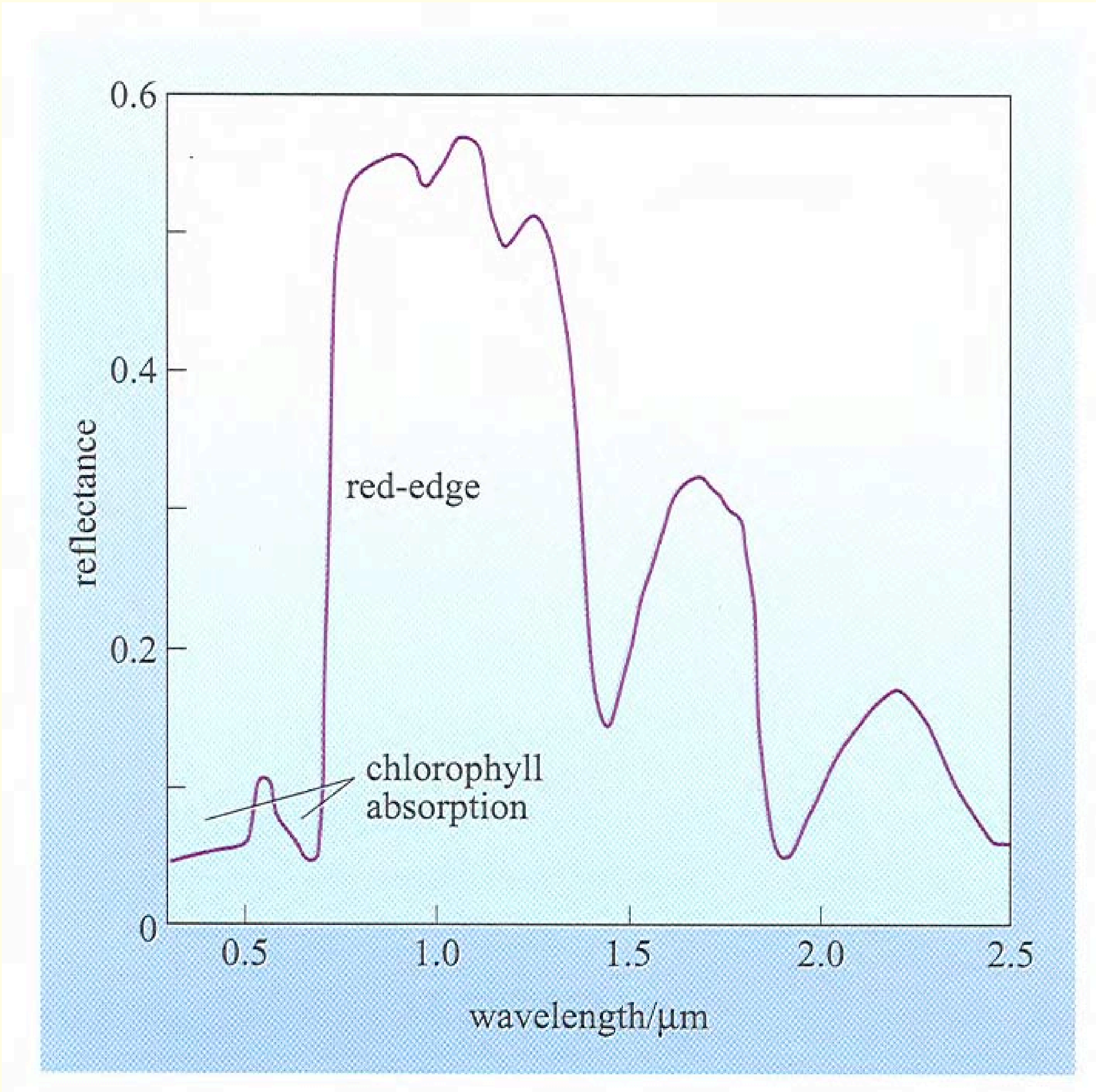
Trace gases in the Earth's infrared thermal spectrum. Composite is in upper right.



Plausible IR spectrum of Earth-like planet 10 pc away as observed by TPF/Darwin for 40 hour exposure. Notice that the poor resolution is the major problem for detecting many biomarkers. Still, many think that simultaneous detection of H_2O and O_3 would be strong evidence.



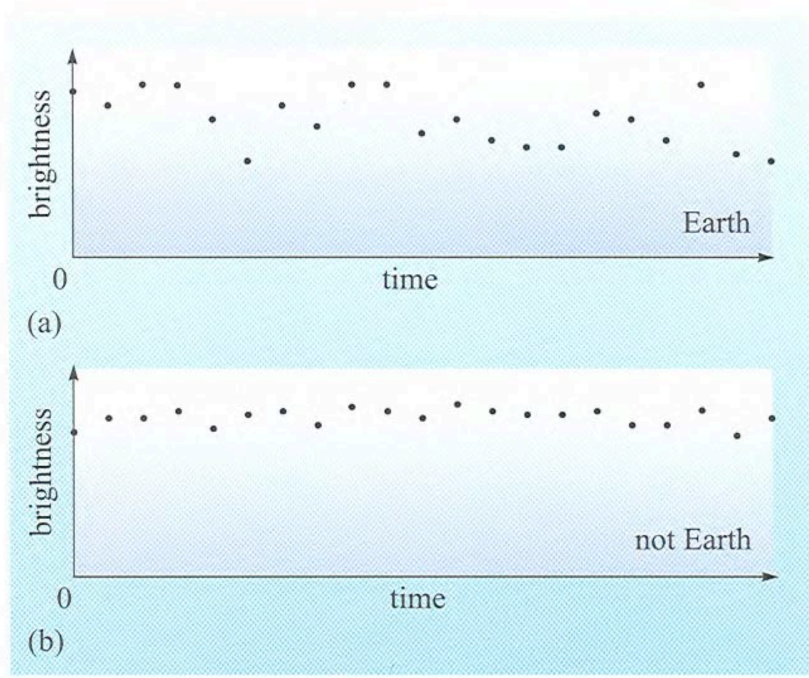
Another suggestion: the **reflection** spectrum in the **visible** part of the spectrum could show the "red edge" exhibited by most vegetation (on Earth!)



Maybe we could learn about a planet without a spectrum (i.e. photometry only). This is possible in the visible because the albedo (fraction of reflected light varies for different materials (left below). Or variation could distinguish continents from oceans (right). So observe light in a few wavelenth bands as a function of time (light curves).

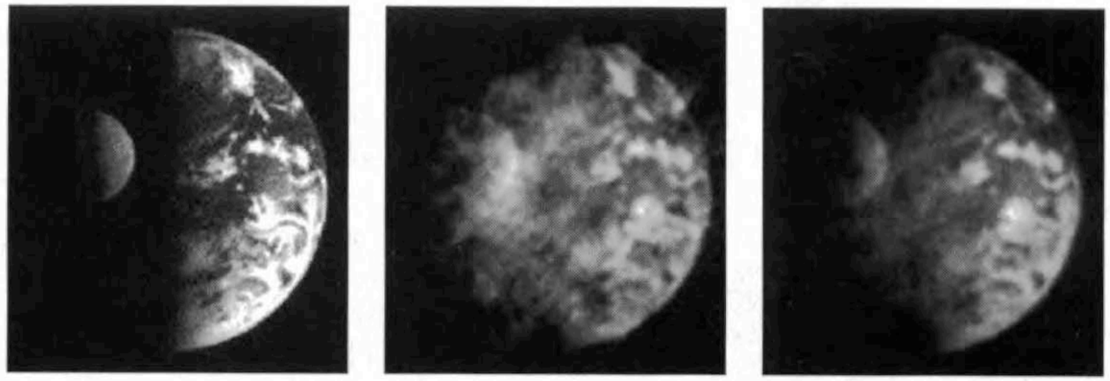
Typical Albedos of Terrestrial Materials

Material	Albedo (Percent)
Earth system as a whole	30
Sand	25
Dense Forest	8
Field crops	25
Water (sun near horizon)	40-75
Water (sun overhead)	6
Fresh snow	85-95
Concrete	20-30



Light curves that typify the sunlit hemisphere of (a) the Earth and (b) a terrestrial body with a more uniform surface.

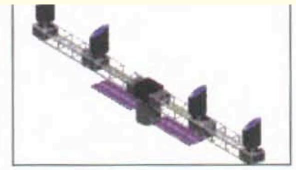
Top: Earth as would be seen by instrument somewhat larger than TPF
Bottom: Earth at night



Imaging Earth. Views of home close up *(left)* and from 10 light-years away taken with a hypothetical interferometer with a 150-kilometer baseline and 48 telescopes *(center)* and 150 telescopes *(right)*.

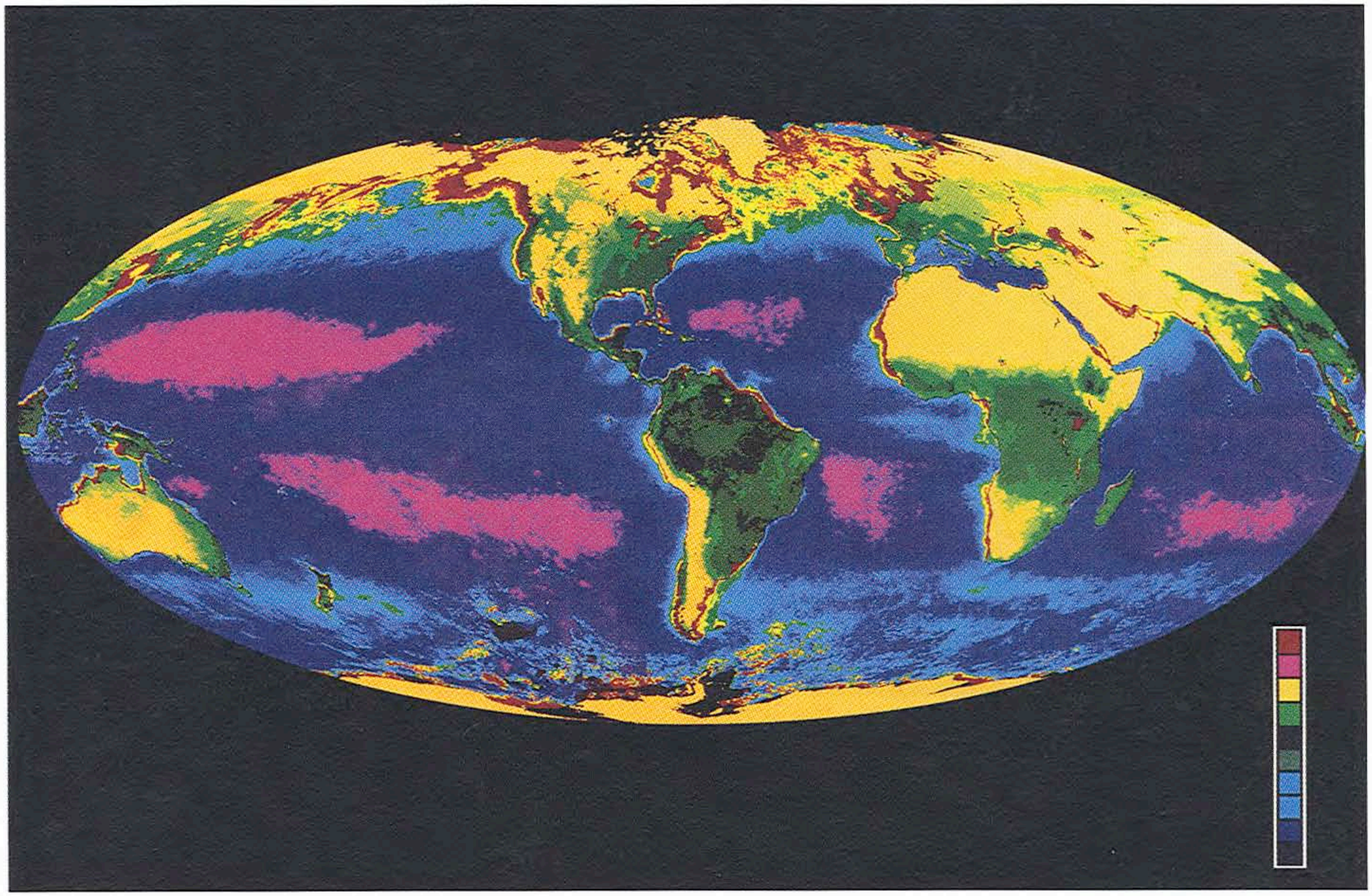
Future space missions for detection of terrestrial-mass planets. Note: ISI=Darwin, similar to TPF and will probably be combined. Planet Imager is still on drawing board.




Mission name	Deep Space 3	Space Interferometry Mission	Infrared Space Interferometer	Terrestial Planet Finder	Planet Imager
Agency	NASA	NASA	ESA	NASA	NASA
Baseline	1 km	10 m	50 m	100 m	6000 km
Resolution (mas)	0.1	0.001	50	25	0.0003
Waveband (micrometers)	optical	optical	7–17 Infrared	7–17 Infrared	7–17 Infrared
Function	Technology demo	Star wobble	Family portrait	Family portrait	Planet images
Launch Date	2002	2005	2009	2010	2020

The ultimate direct detection: not likely in next two decades (see figure caption).



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)