Hunting for Extrasolar Planets: Methods and Results (Sec. 11.2 in your textbook)

Remember motivation: No life without planet, and not just any planet--must be planet within factor of ten of Earth's mass.

There are over 300 exoplanets currently known. By the end of this section you should know a little about each of the detection methods listed below, and why only one of them is responsible for nearly every detection (so far)

INDIRECT OBSERVATION

Astrometric method (stellar wobble)-- image of star

Radial velocity (Doppler)-- spectrum of star

Transit photometry -- light curve of star

Gravitational lensing -- light curve of star

Pulsar timing -- another photometric method, using *timing*

DIRECT OBSERVATION (IMAGE OF PLANET)

VERY large telescopes

Interferometers

How to define "planet"?
In terms of mass, *and* the way in which it formed

Star: massive enough for nuclear fusion H ➔ He

M > 0.1 Msun

- Luminosity comes from heating by nuclear fusion.

Brown dwarf: mass too small for nuclear fusion.

M < 0.1 Msun (~ 80 Mjup)

- Luminosity from slow contraction, release of gravitational energy.
- Probably form in similar manner as stars.

Planet: Upper limit usually taken as ~ 10 - 20 MJup.

Lower mass limit not too important because we couldn't detect it. Mars counts as a planet (0.1 Mearth), Pluto doesn't.

- Most of their luminosity is reflected light from their parent star, plus a smaller amount coming from their own thermal infrared radiation.
- We assume they all form from disks surrounding young stars.

It has become traditional to classify extrasolar planets as what they resemble most in our own solar system. So: Jupiters (or "gas giants"); Neptunes (~ 20 M_{earth}); and (more recently) Super-Earths (~ 5-10 M_{earth}). When we refer to (yet to be discovered) extrasolar planets whose masses are similar to Earth, they are called "terrestrial-like" or "Earth-like" or "rocky" planets.

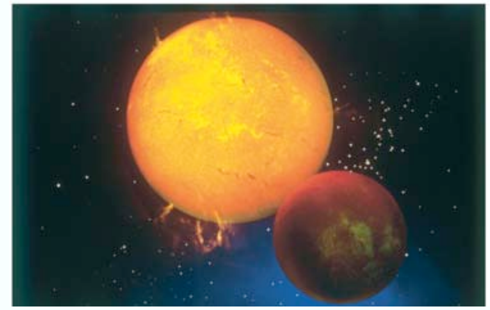
How to define a “planet”?? By mass, but what mass? By how it formed, but how would we know how something formed?

	STARS	BROWN DWARFS	GIANT PLANETS	TERRESTRIAL-LIKE PLANETS
	O star … Sun… M star	(BD limit)	Jupiter	Earth
Mass (solar units)	$100M_{\odot}$ … 1 … $0.08M_{\odot}$	… ?	… 0.001	… $0.000003M_{\odot}$
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

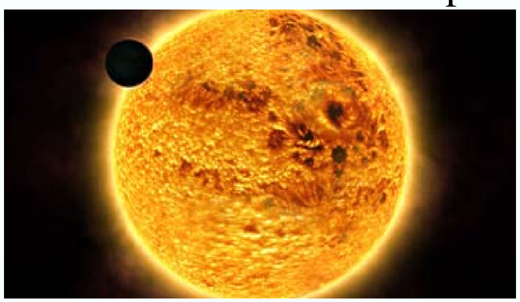
Why are pictures of extrasolar planets always "artists' conceptions" if so many exoplanets have been discovered? Because we can only detect them *indirectly*, NOT by direct imaging

Evaporating hot Jupiter

Recently-discovered triple Super-Earth

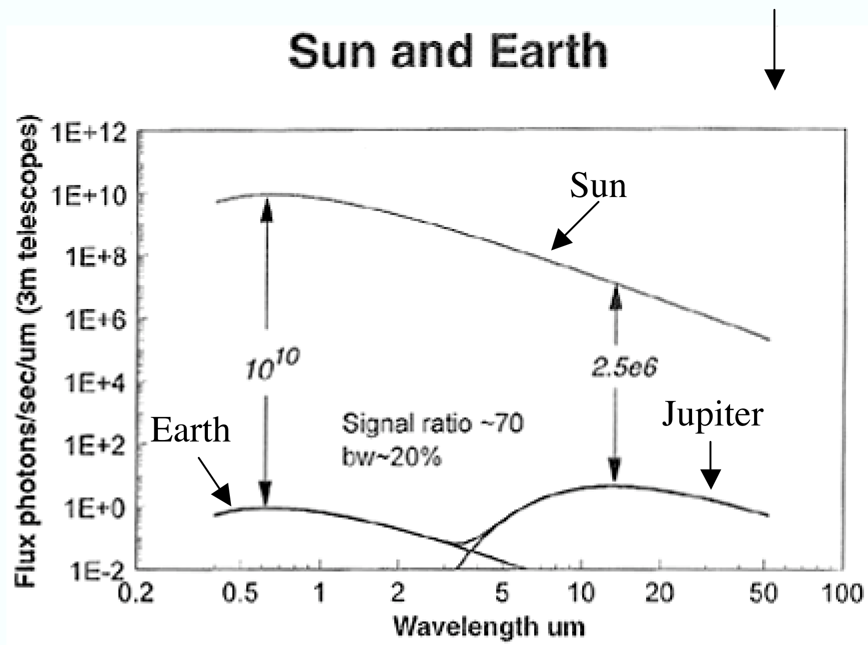


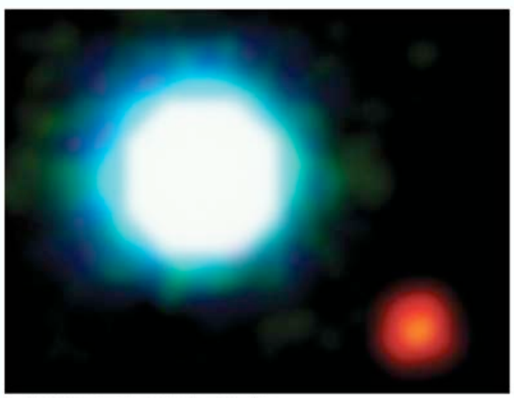
Another close-in gas giant



A transiting exoplanet

Direct detection: currently not feasible except for extremely massive planets

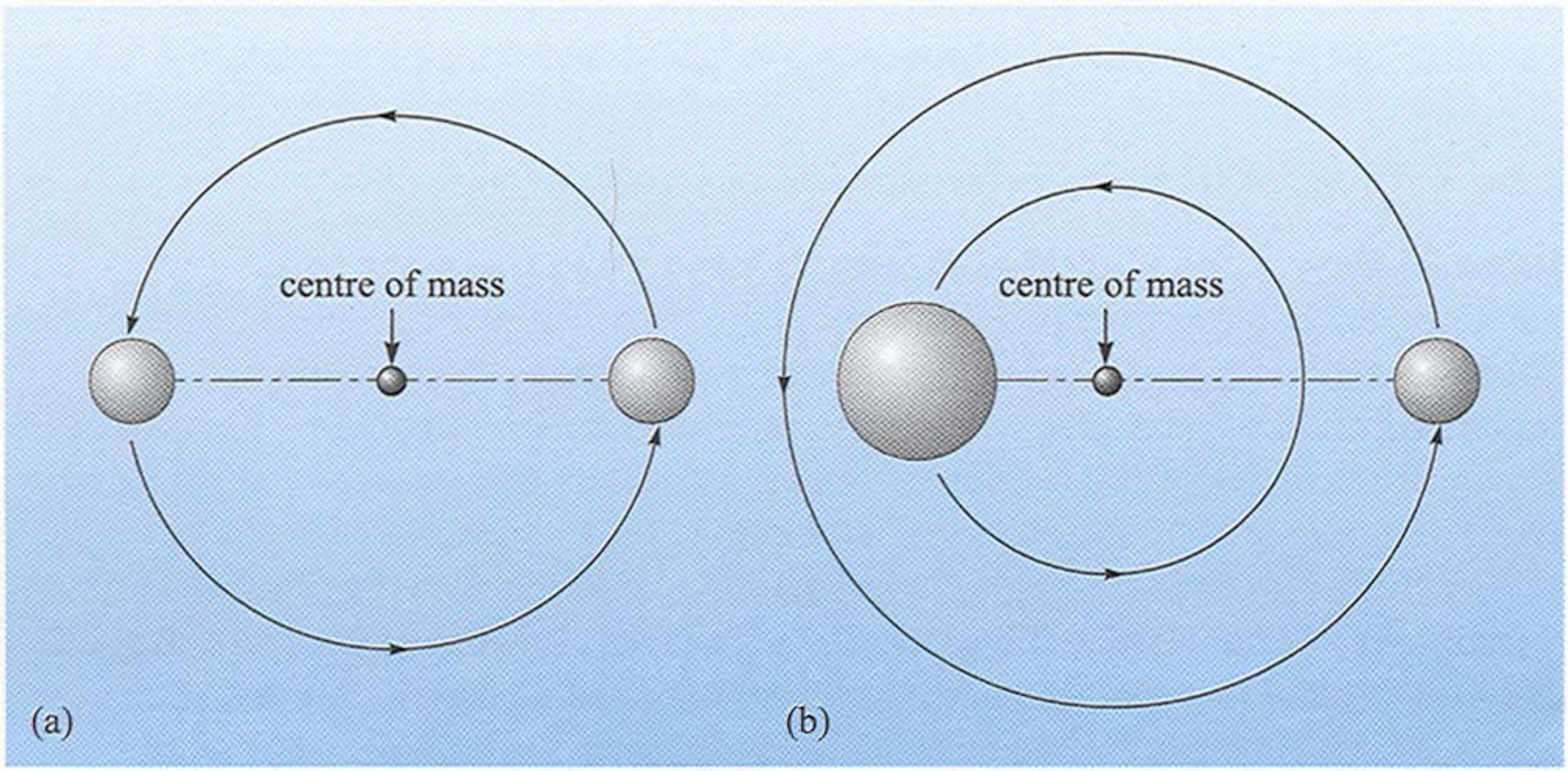




A "real" direct detection:
Probably a brown dwarf, not a planet

Principle behind several methods of exoplanet detection

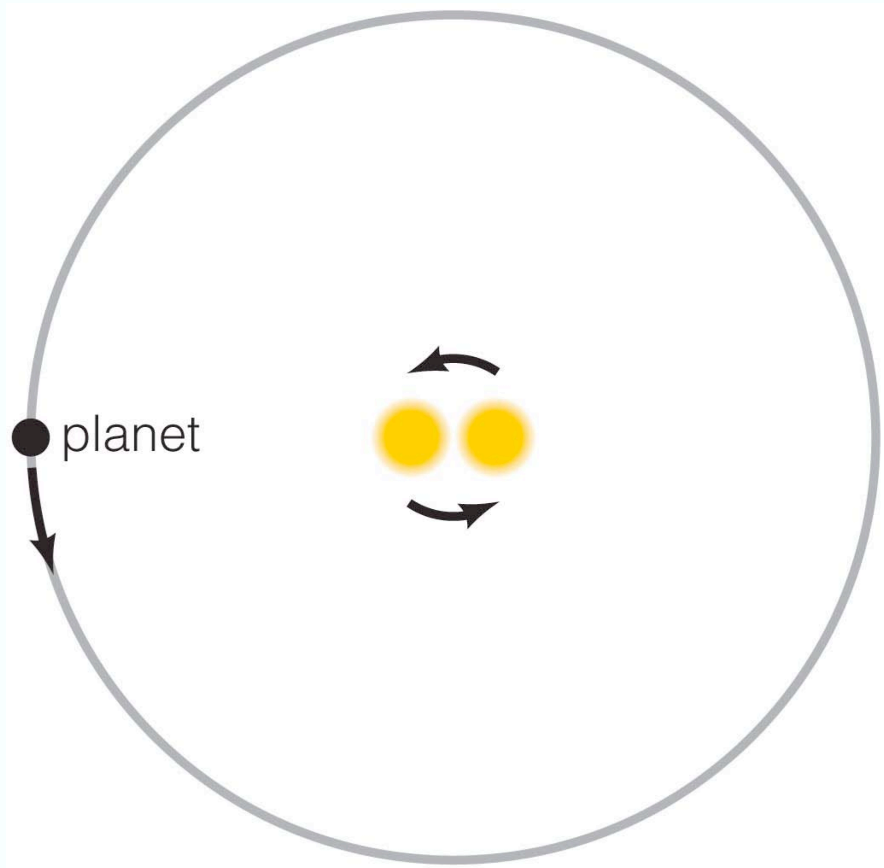
Two objects orbit their ***center of mass***, or "barycenter." The barycenter is closer to the more massive object (star) than the less massive object (planet). A star is so much more massive than a planet that the barycenter is very close, or even inside, the star



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.

Center of mass (continued)

In the extreme case where one of the objects is much less massive than the other, the center of mass is very close to the more massive object, so more difficult to detect its motion.



Example: Jupiter and the Sun

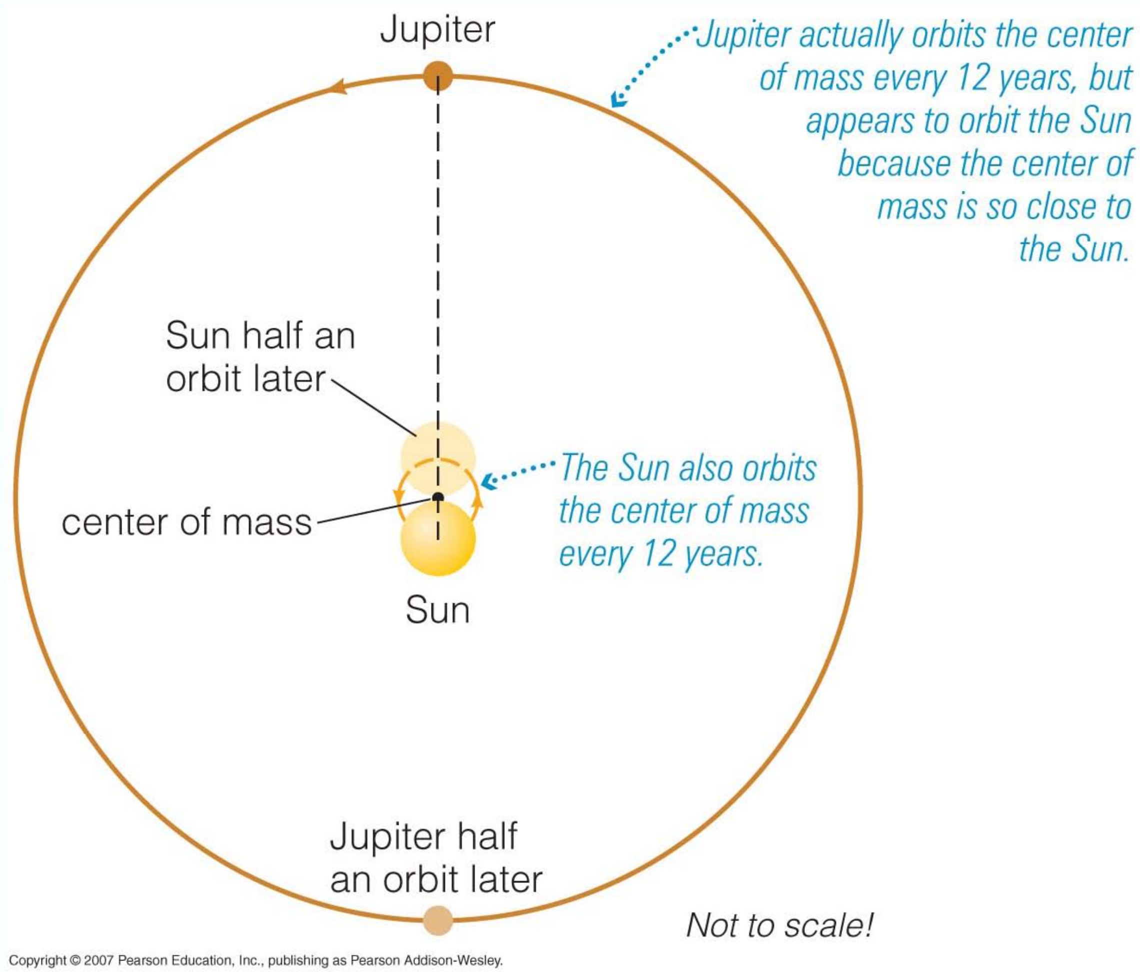
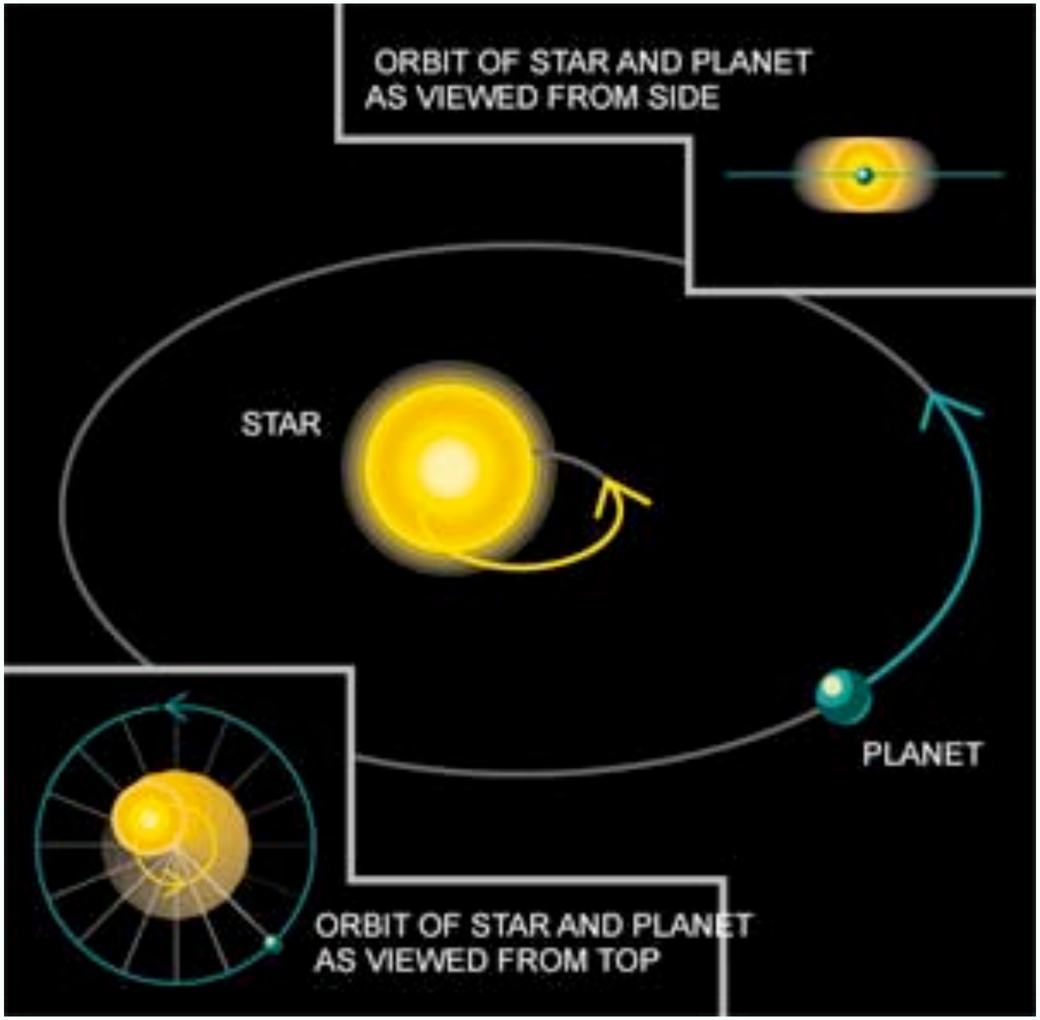
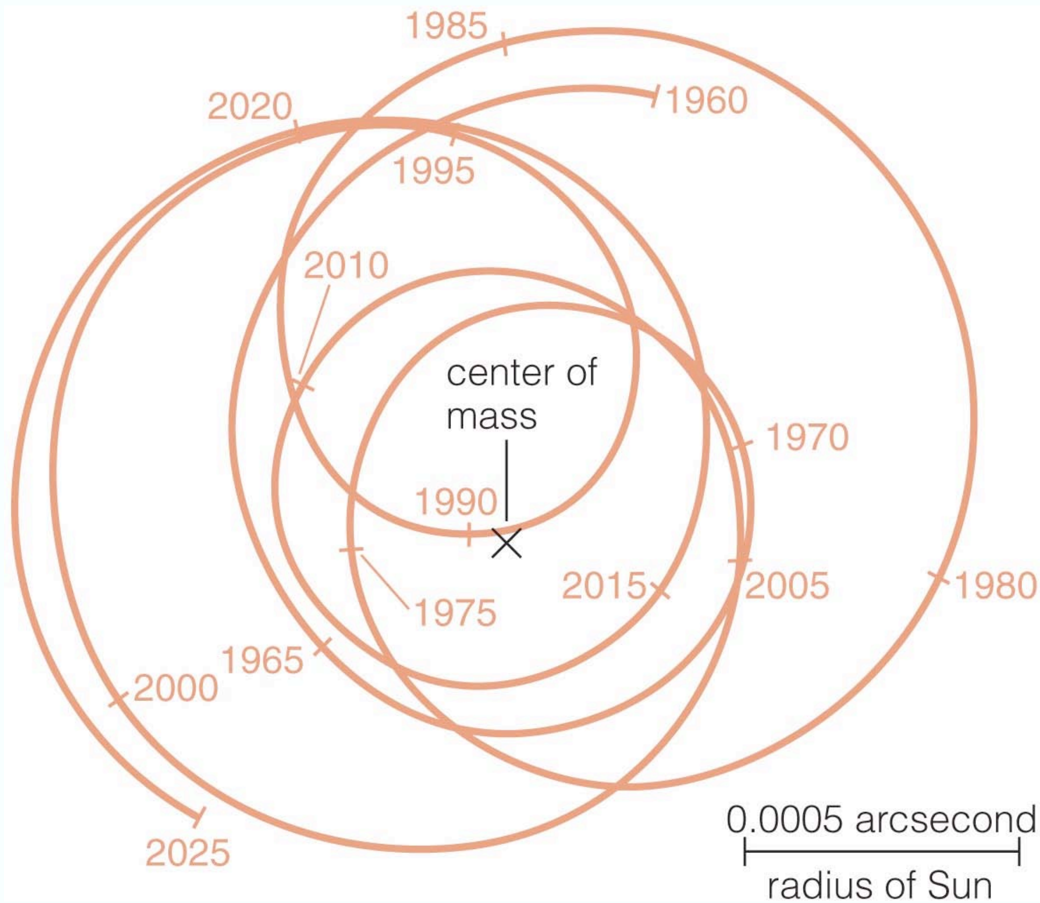


Fig. 11.5 in textbook

Star and Planet Orbit Center of Mass: Consider viewing angle (*inclination* of orbit)

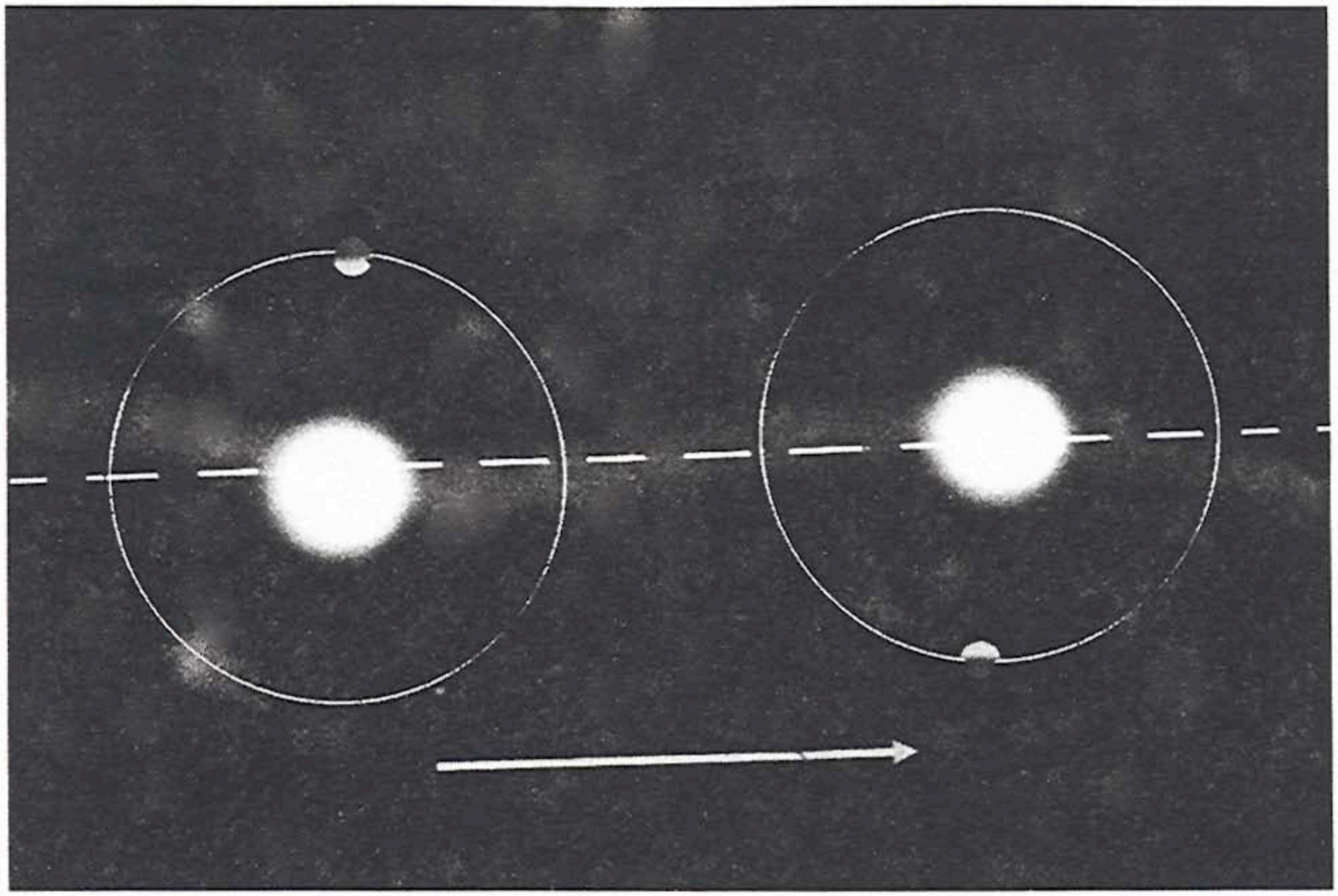


Motion of Sun due to gravity of all the planets (mostly Jupiter)



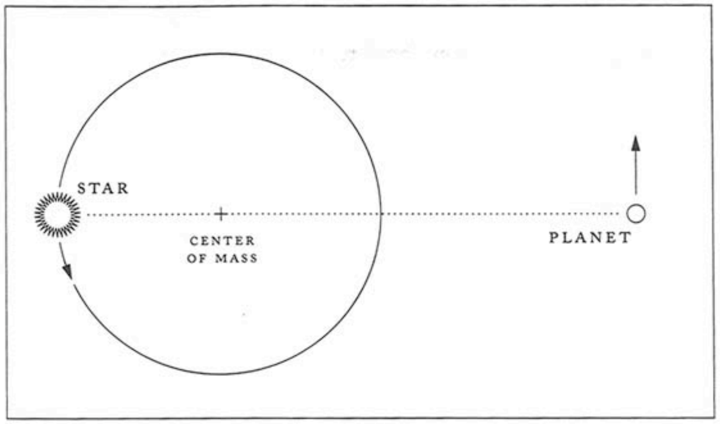
- Fig. 11.8 in textbook

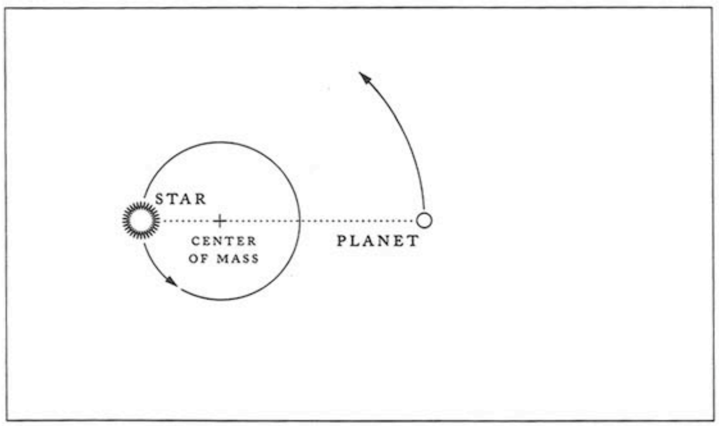
Astrometric method: Must detect very small "wavy" motion of the star along its path (milli- or even micro- arcseconds) in the sky. Extremely difficult, and most sensitive to planets far from star, so takes many years. Future space mission SIM detect thousands of planets using this method (see pp. xxx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



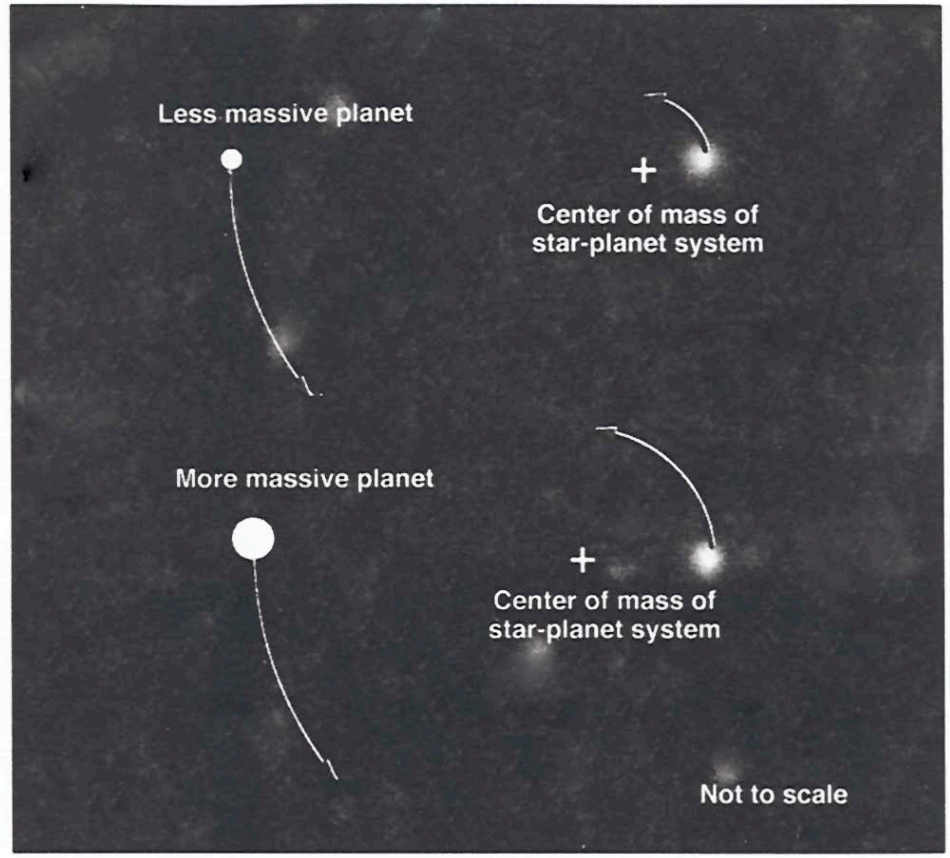
If we can measure a star's apparent motion through space with sufficient accuracy, we can hope to observe the deviations from straight-line motion that the gravitational force from a planet or planets orbiting the star will produce.

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





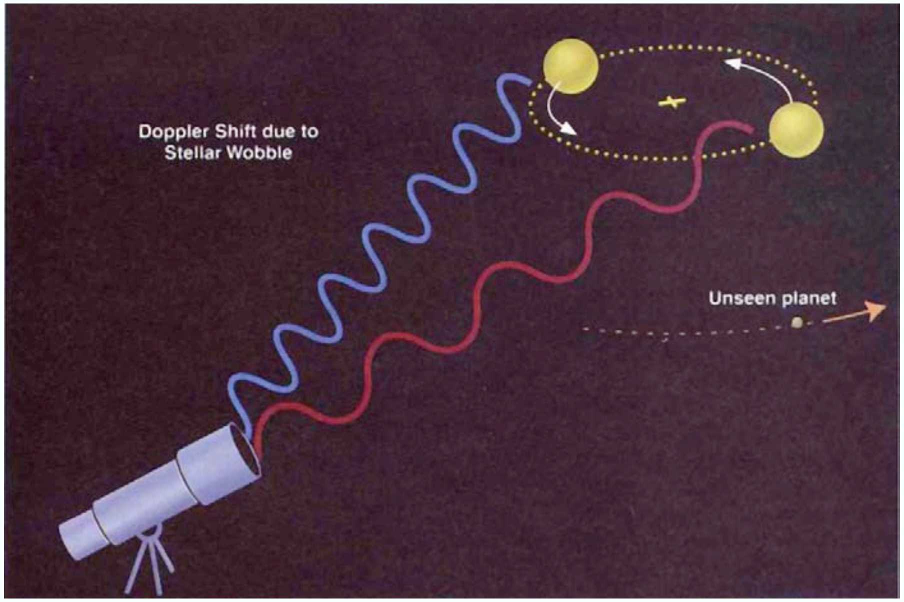
If a planet lies far from its star (top), the star will execute a large wobble around the center of mass, a wobble that astrometrists have a chance to detect; but the star will move only slowly, so Doppler observers, who measure stellar speeds, will fail. On the other hand, a star with a close-in planet (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.

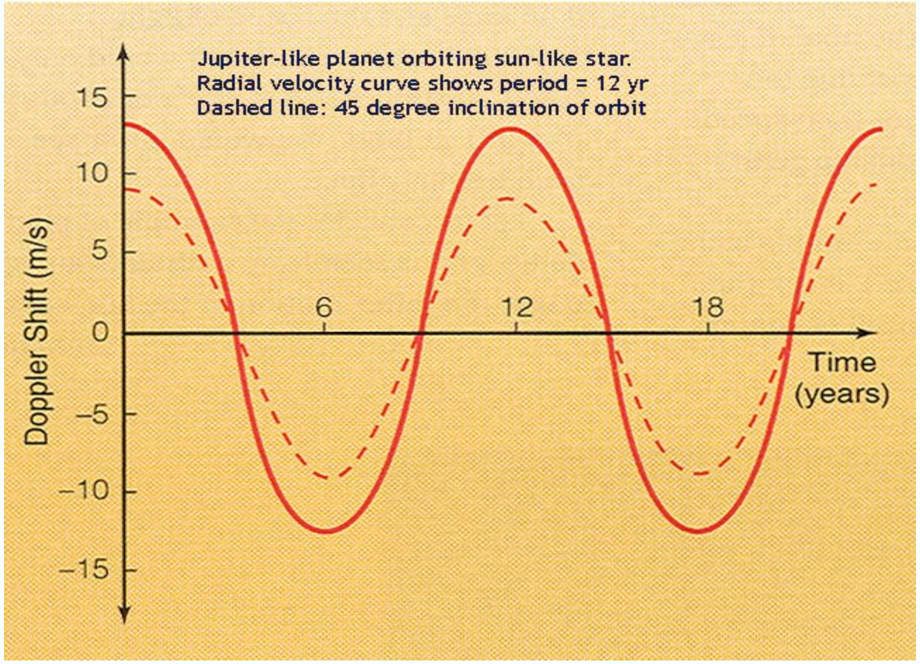


A planet orbiting at a specific average distance from its star will produce changes in the star's velocity that are greater for planets with larger masses. This fact allows astronomers to deduce the mass of the planet once they estimate the mass of the star and have derived the average distance at which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

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

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

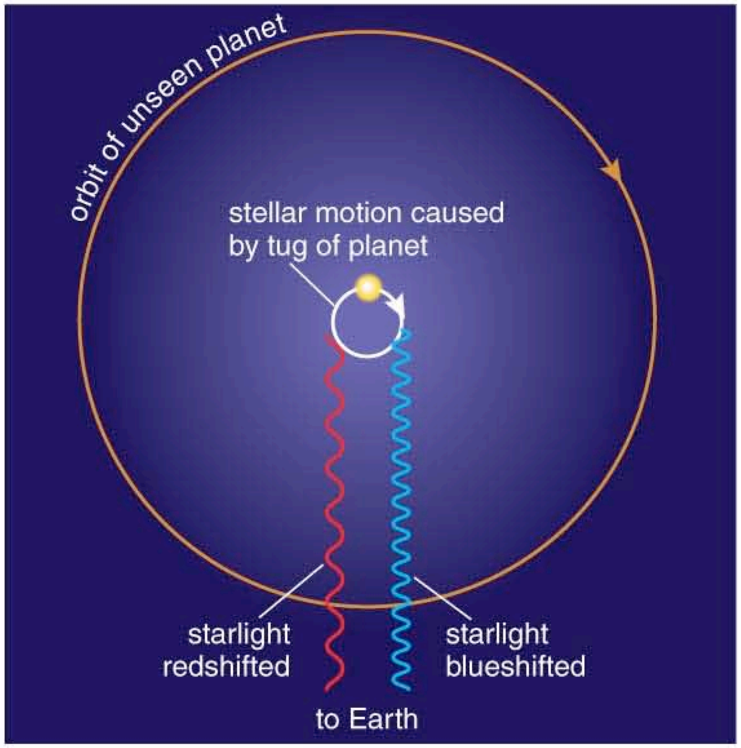




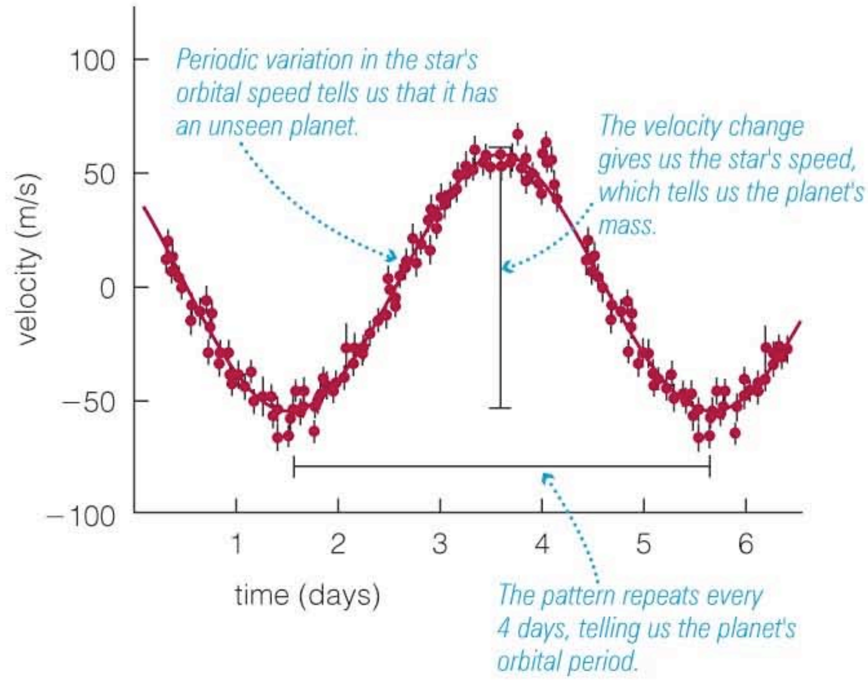
Next 12-15 slides are about the radial velocity method and the results from its use: Nearly all known exoplanets were detected using r.v. method

Also see Figures in textbook

Textbook version of previous figures



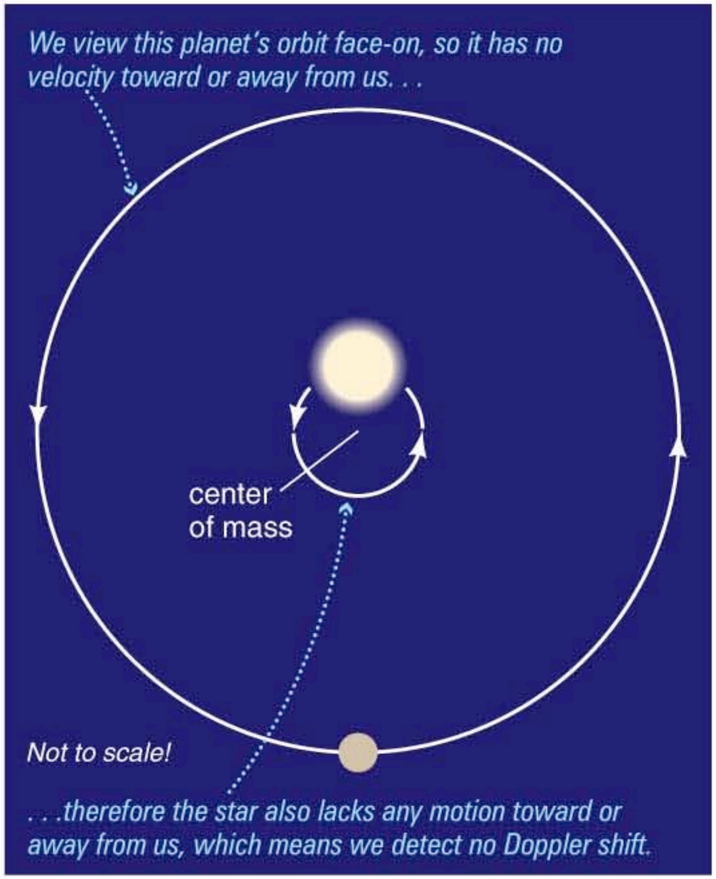
a Doppler shifts allow us to detect the slight motion of a star caused by an orbiting planet.



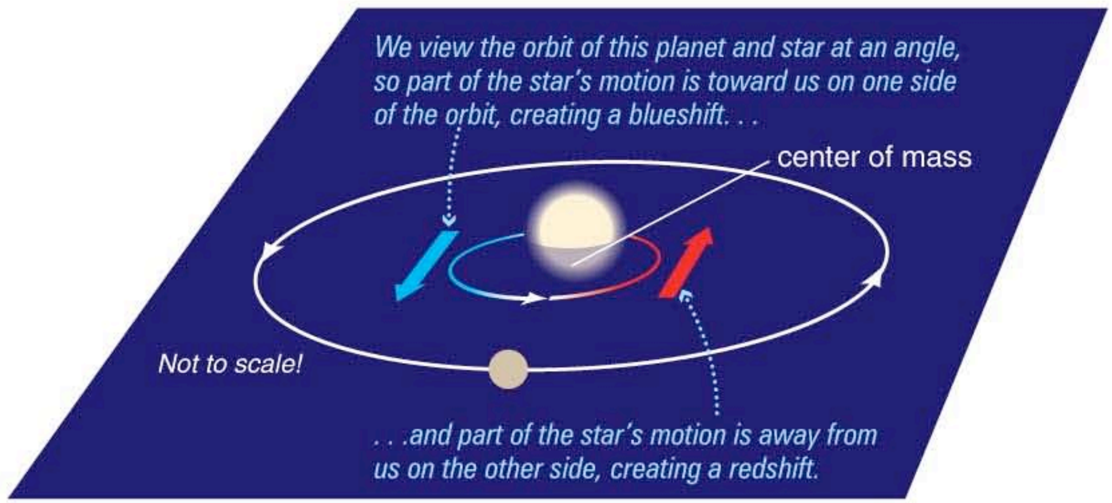
b A periodic Doppler shift in the spectrum of the star 51 Pegasi shows the presence of a large planet with an orbital period of about 4 days. Dots are actual data points; bars through dots represent measurement uncertainty.

Radial velocity method: Effect of inclination

Speed of star, and so mass of planet, depends on **inclination** of the orbit: 90 degrees gives full speed, but in general see only part, so get *lower limit* to mass of planet



a If we view a planetary orbit face-on, we will not detect any Doppler shift at all.



b We can detect a Doppler shift only if the planet and star have some part of their orbital velocities directed toward or away from us. The more the orbit is tilted toward edge-on, the greater the shift we'll observe.

- Figs. 11, 12 in Ch. 11 of textbook.

Comparison of two search methods

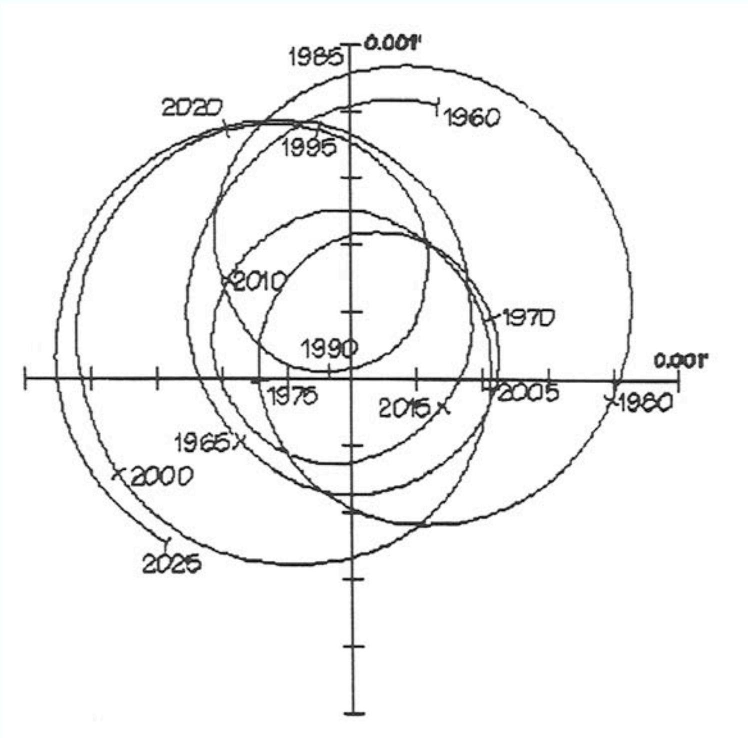
Advantages

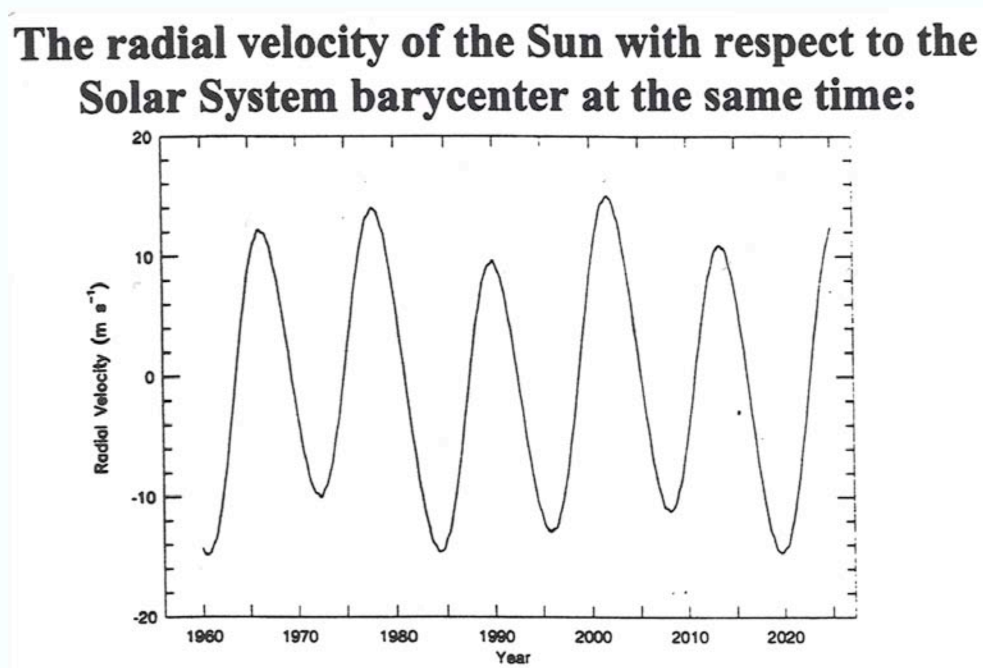
Astrometric	Spectroscopic
Big Planet	Big Planet
→ Big Orbit	Small Orbit
Small Star	Small Star
Nearby Star	--
Face-on Orbit	Edge-on Orbit

(Spectroscopic = radial velocity method)

Why the radial velocity method was not expected to be successful without several years of observations:

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*!

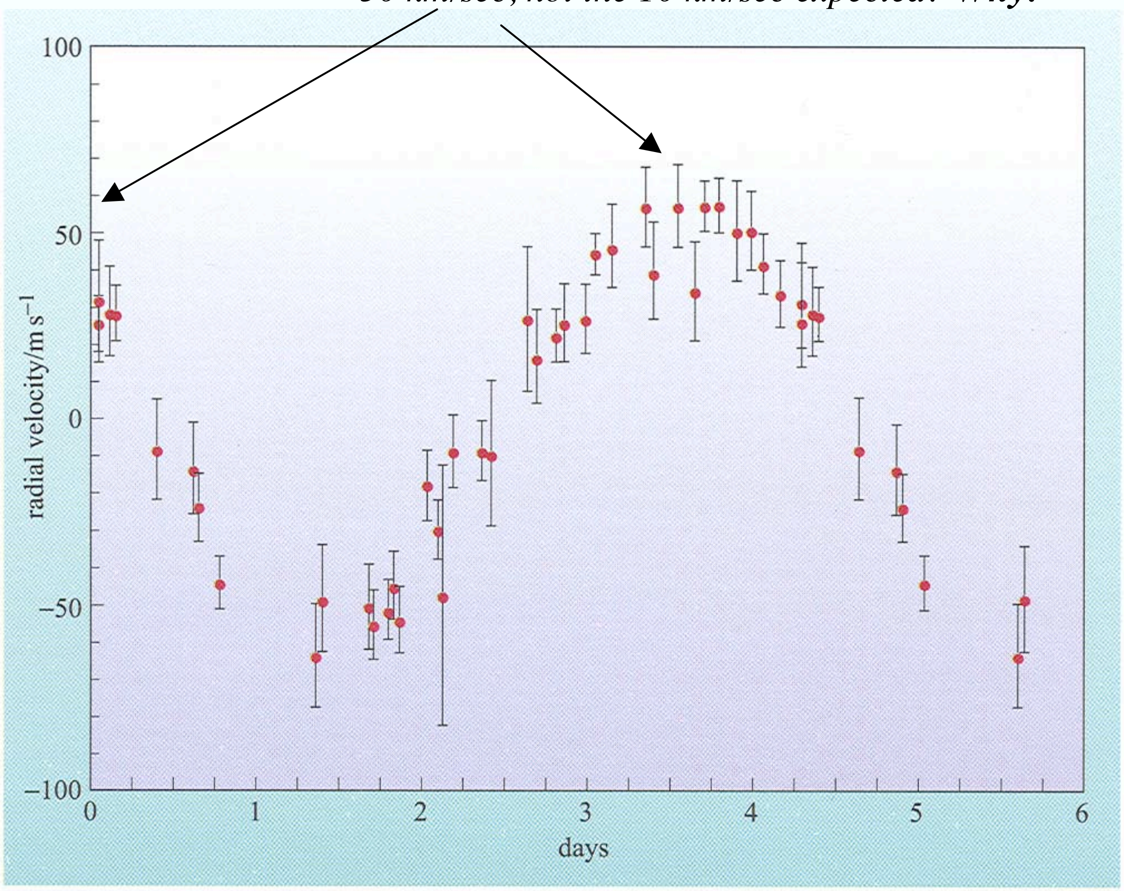


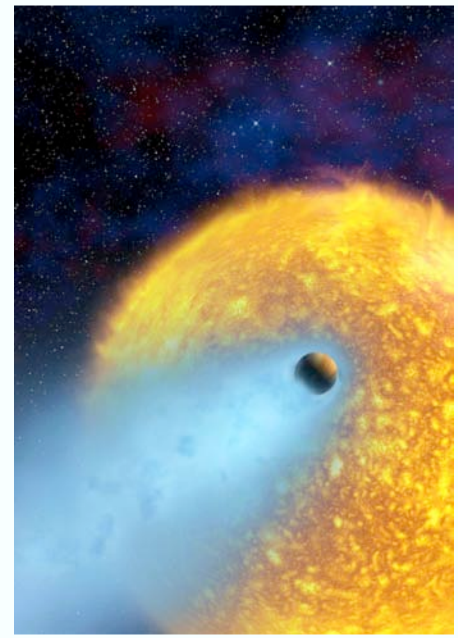


First big surprise from exoplanet detection: Hot Jupiters (close-in gas giants)

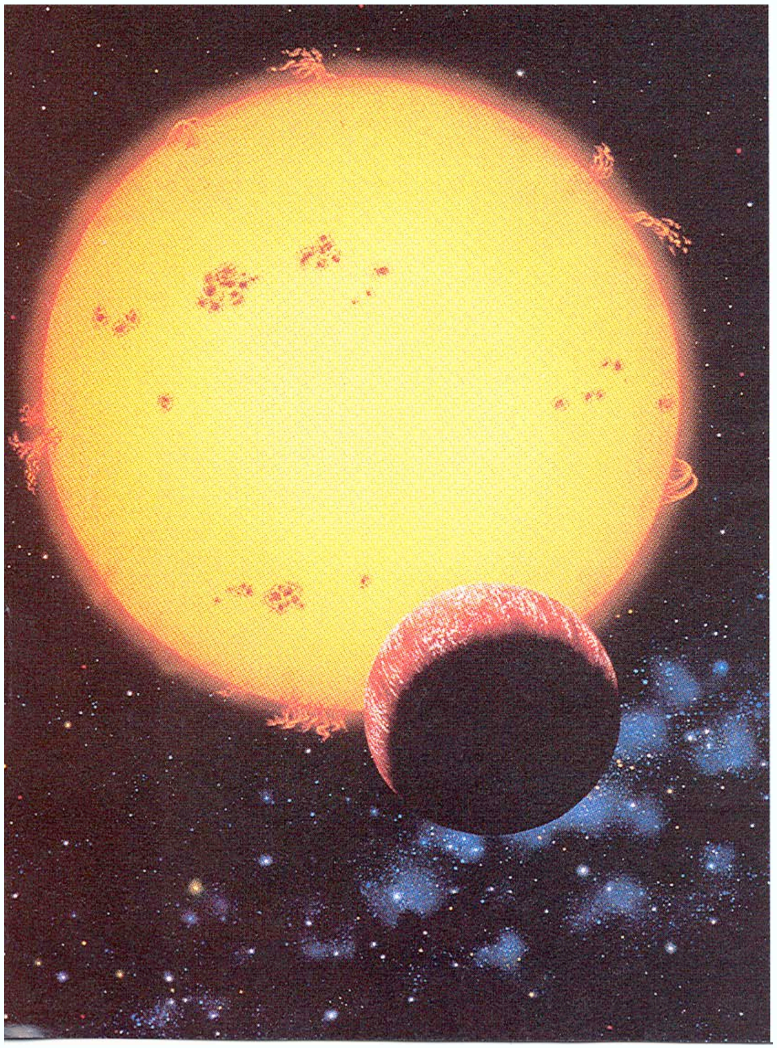
Big surprise in 1995: Radial velocity curve of star 51 Pegasi shows *large* radial velocity amplitude and orbital period of *days*, not years! Must be giant planet *very* close to its parent star. Planet is evaporating as it spirals into its parent star.

Notice radial velocity amplitude is over 50 km/sec, not the 10 km/sec expected. ***Why?***





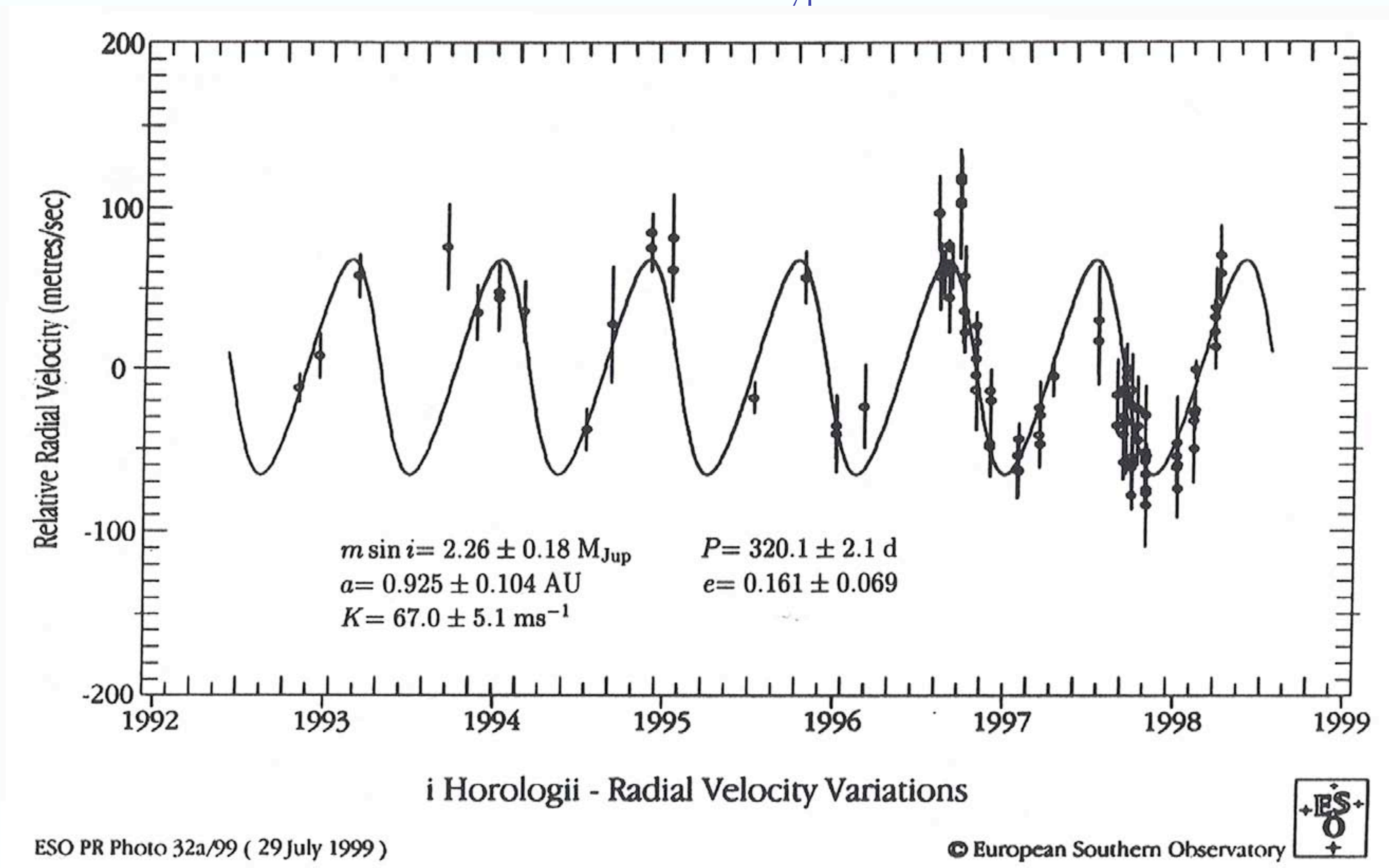
Hot Jupiters or close-in giant planets (cont'd)



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? (It can't)
➞ direct evidence for ***planetary migration***

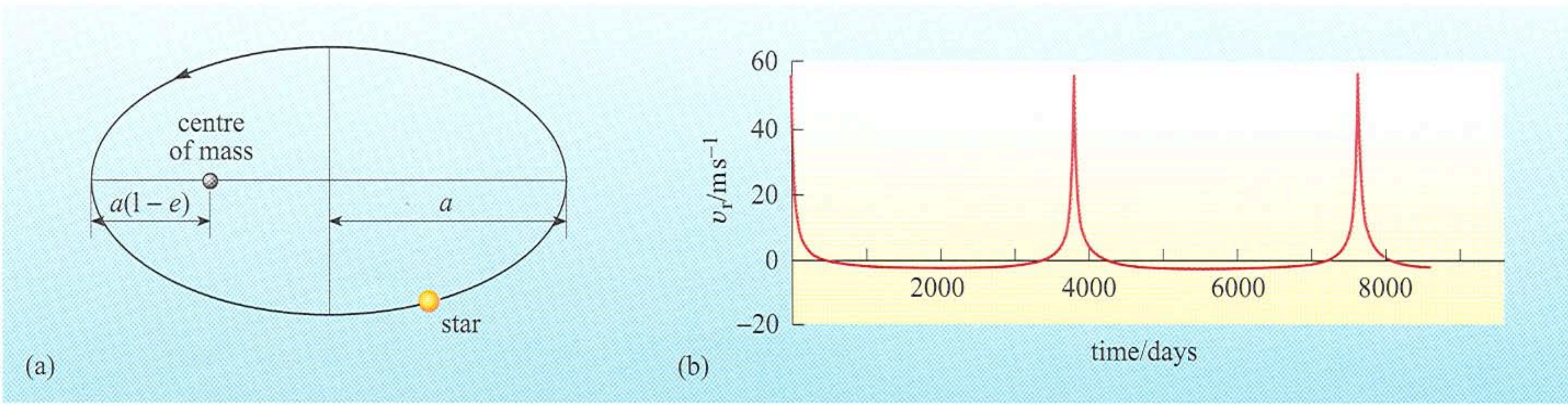
If most stars form planetary systems in which giant planets migrate, any Earth-like planets that form may be expelled from the system, or might not ever form.
➞ *What is the chance of this happening?*

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, first sparse, then, when it is clear a that the variation is periodic, much more telescope time granted to fill in the r.v. curve--this is typical.



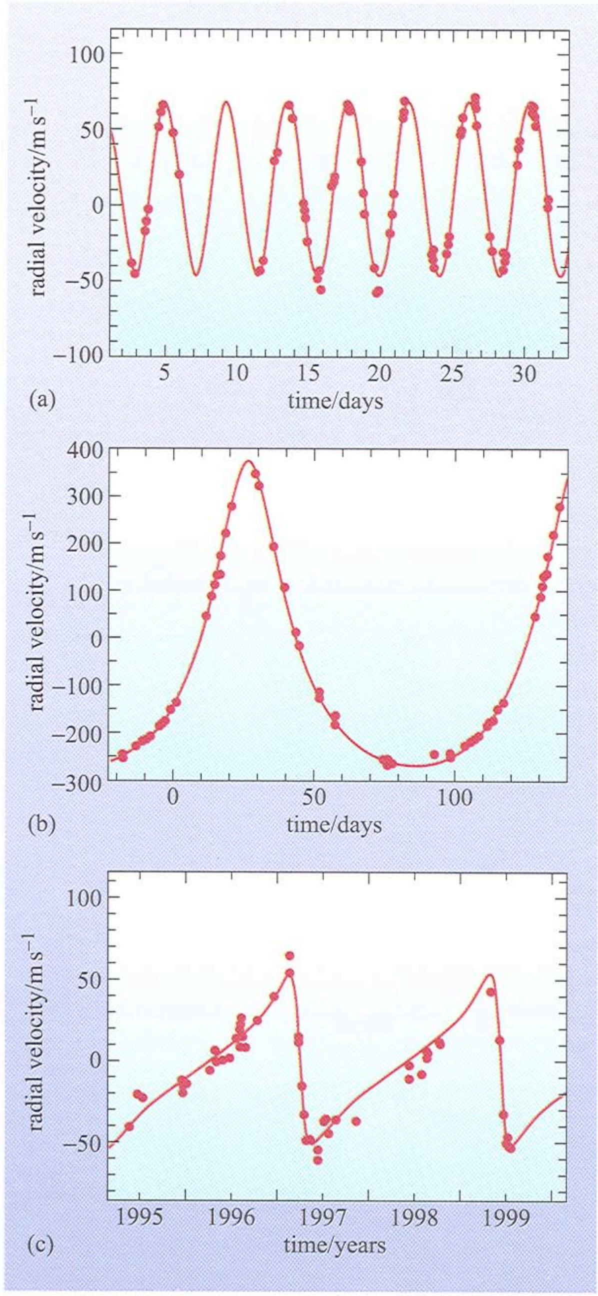
Exoplanet eccentricities: Finally a use for Kepler's 2nd law

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).

See corresponding illustration and discussion in textbook

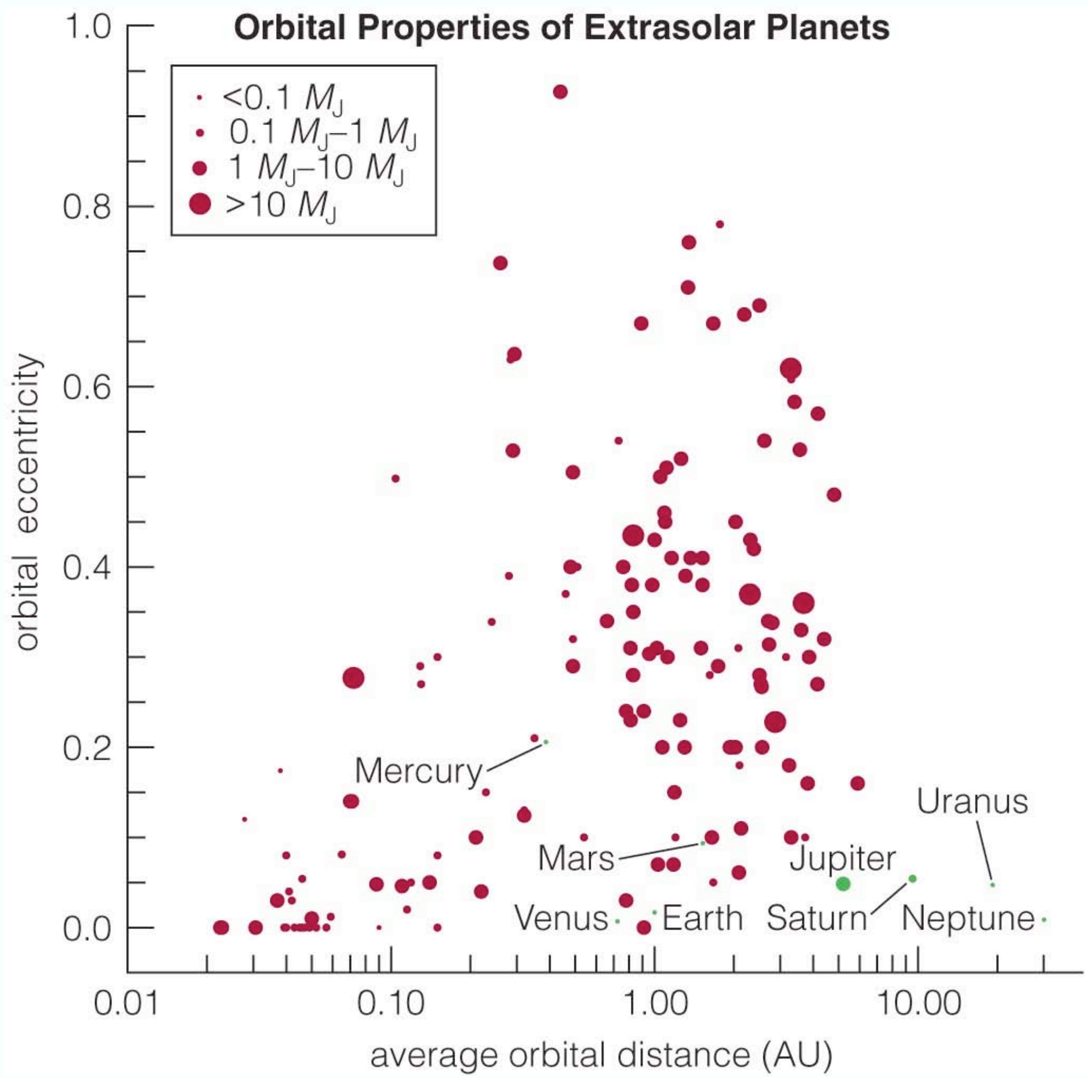


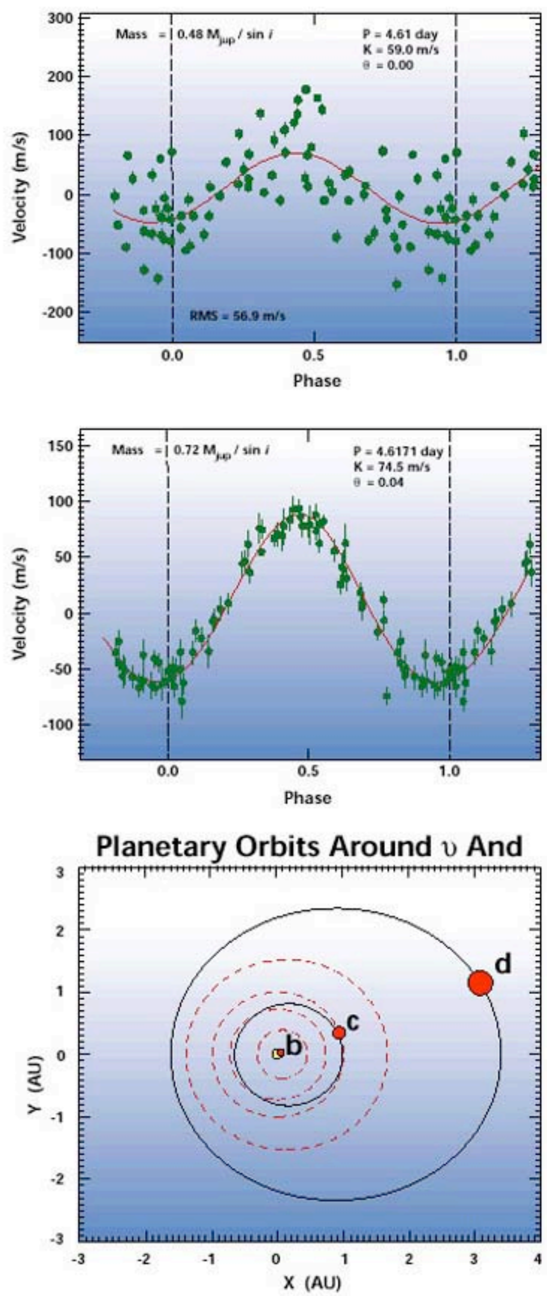
Exoplanet eccentricity (continued)

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: Eccentric Jupiters "kick" small terrestrial-like planets out of the system.

Eccentricity vs. semimajor axis (distance from parent star) for many of the known giant exoplanets (Fig. 11.17). Large number of gas giants with large eccentricities! (Notice Earth is at 1 AU, Mercury at 0.4 AU from Sun.) But orbits should be "circularized" in a very short time. Question still not explained.





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).

Planetary *systems*

A landmark in extrasolar planet discovery:
A star with multiple (giant) planets.

So there might be other "solar systems."

Homework assignment:
As of 2008, what is the largest number of planets discovered around any star?

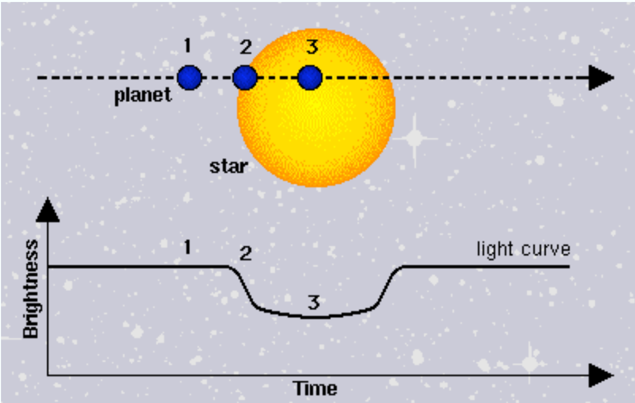
Understand the advantages and disadvantages of the astrometric vs. the radial velocity method. Read about the potential of the future SIM space mission for planet detection in your textbook.

	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

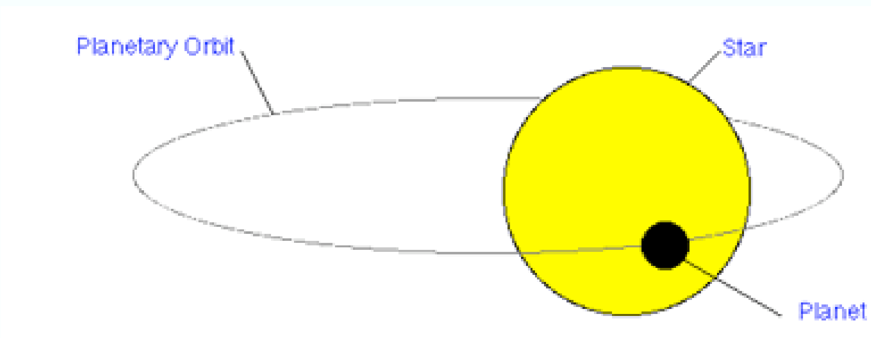
Now on to other methods

The Transit Method

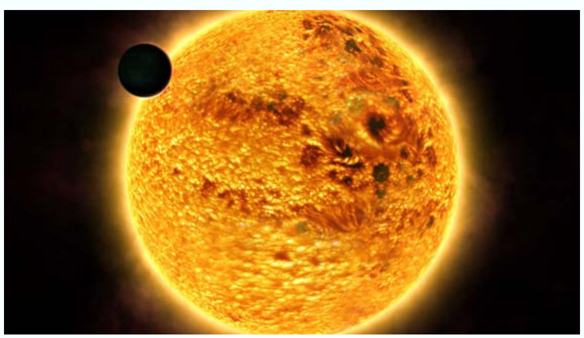
Exoplanet detection: The transit method

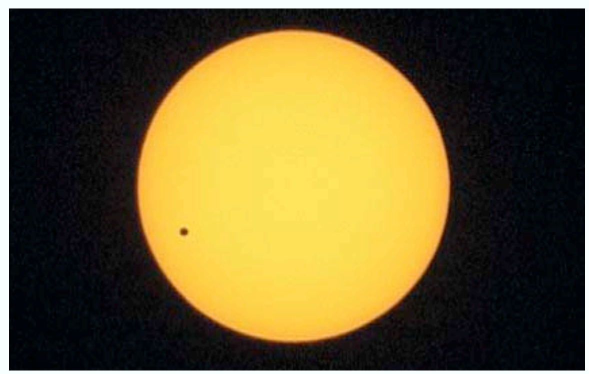


Basic idea: when planet passes in front of star, brightness of star will decrease *a little*. So only need "light curve" from **photometry**, but *very* accurate photometry.



- Inclination must be almost exactly 90 degrees, or planet will not pass in front of the star.
- If transit, then get inclination → can correct mass lower limit obtained from radial velocity method.



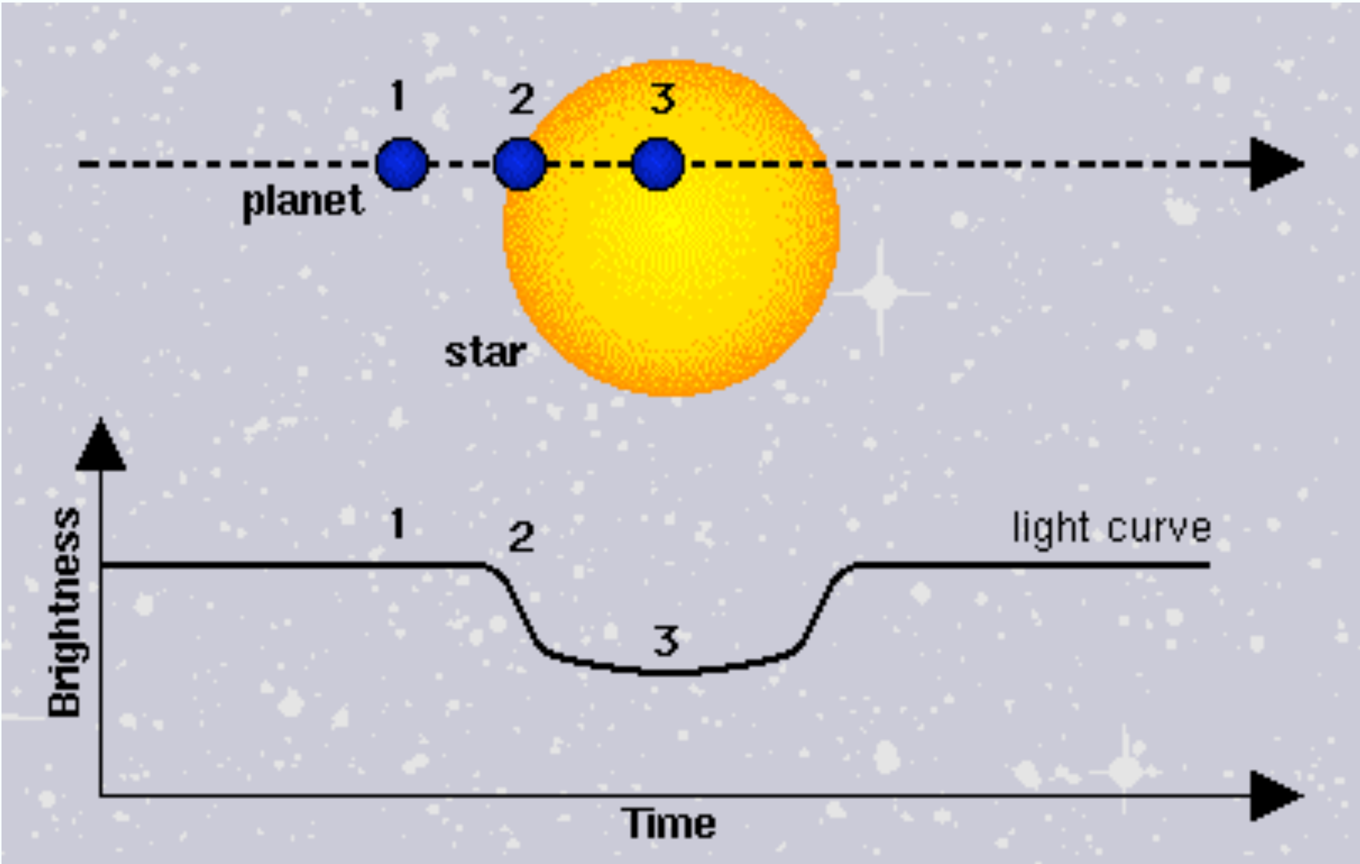


- Transit detection favors large planets, close to star.

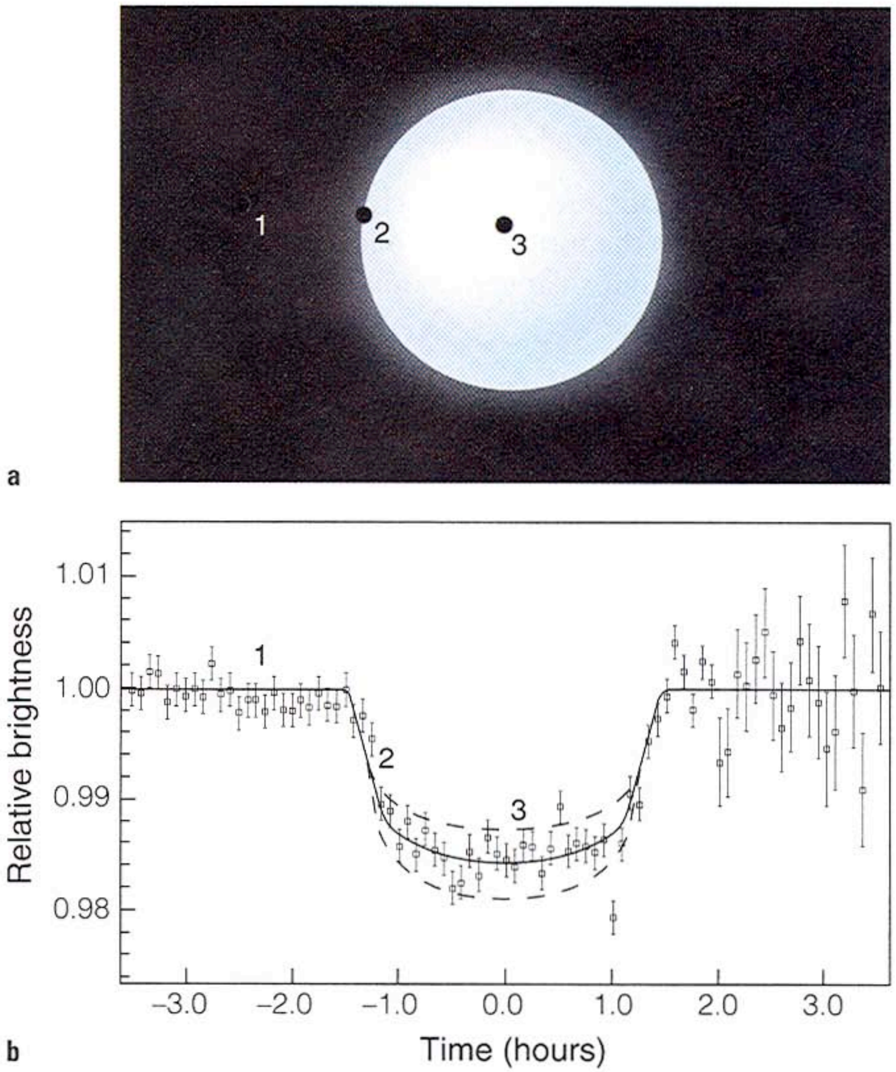
Exoplanet Detection: The Transit Method (cont'd)

A photometric method, not spectroscopic, and not imaging.
Probably the most active area of planet searching today because

- It does *not* require a large telescope!
- Chances of finding a planet-star system nearly edge-on is small, so need lots of observations;
- Big payoff: you can learn about a stars diameter *and* mass, and so get *density*. Also: can observe planet's spectrum!



Light curve of a transit event

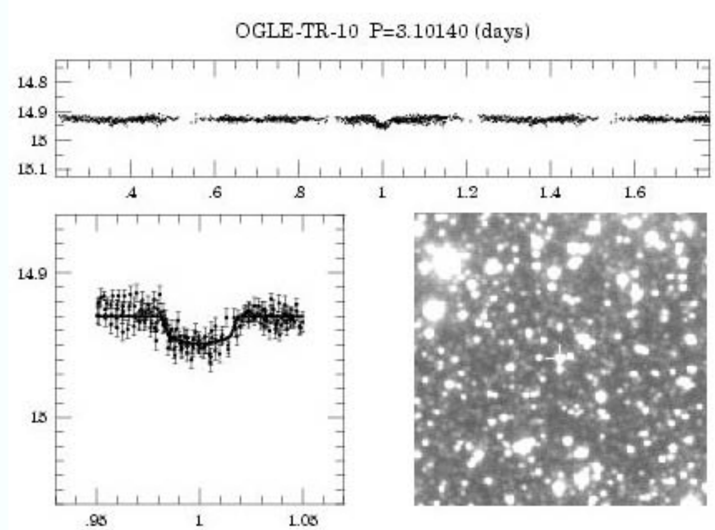


Careful measurements of the brightness of the star called HD209548 revealed that an orbiting planet passes directly in front of it as seen from Earth, which means that the planet's orbit must be edge-on as seen from Earth. (**a**) Artist's conception of the planet as it passes directly in front of its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

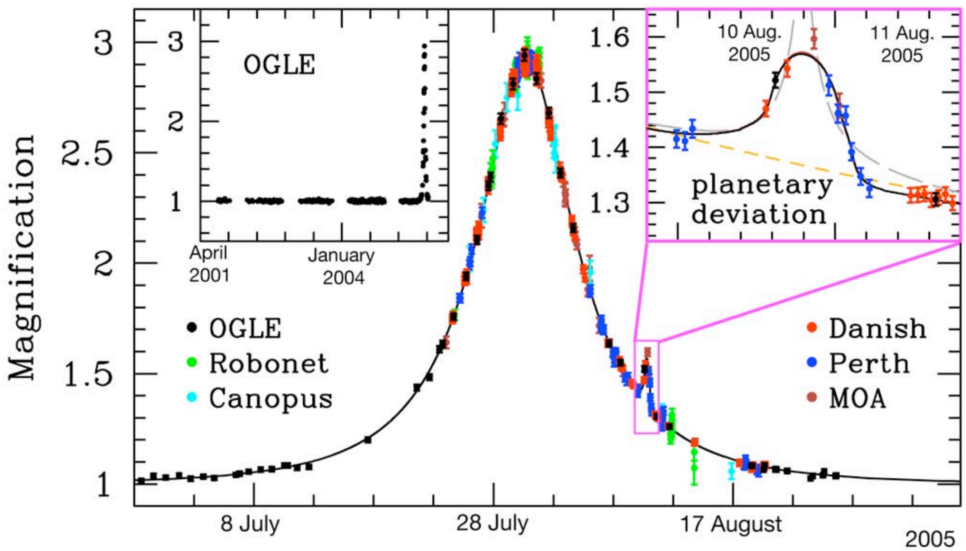
In practice this method is very difficult, because you have to monitor a huge number of stars (most of which won't have suitable planets for transit discovery) *and* the effect you're looking for is extremely small--about 1% for a giant planet, much smaller for terrestrial-mass planets: So must search from space--CoRoT, Kepler.

(Figure to left is from your textbook.)

A real transit detection



Planet Detected by *Gravitational Microlensing*



Light Curve of OGLE-2005-BLG-390

Sharp spike indicates second lens. Mass of second lens only 8 x 10^{-5} as massive as star. Most likely mass of this planet is 5.5 M_{earth} and separation from star is 2.6 AU. Most likely star is low mass (0.22 M_{sun}). *If correct, this is one of lowest-mass planets yet detected.*

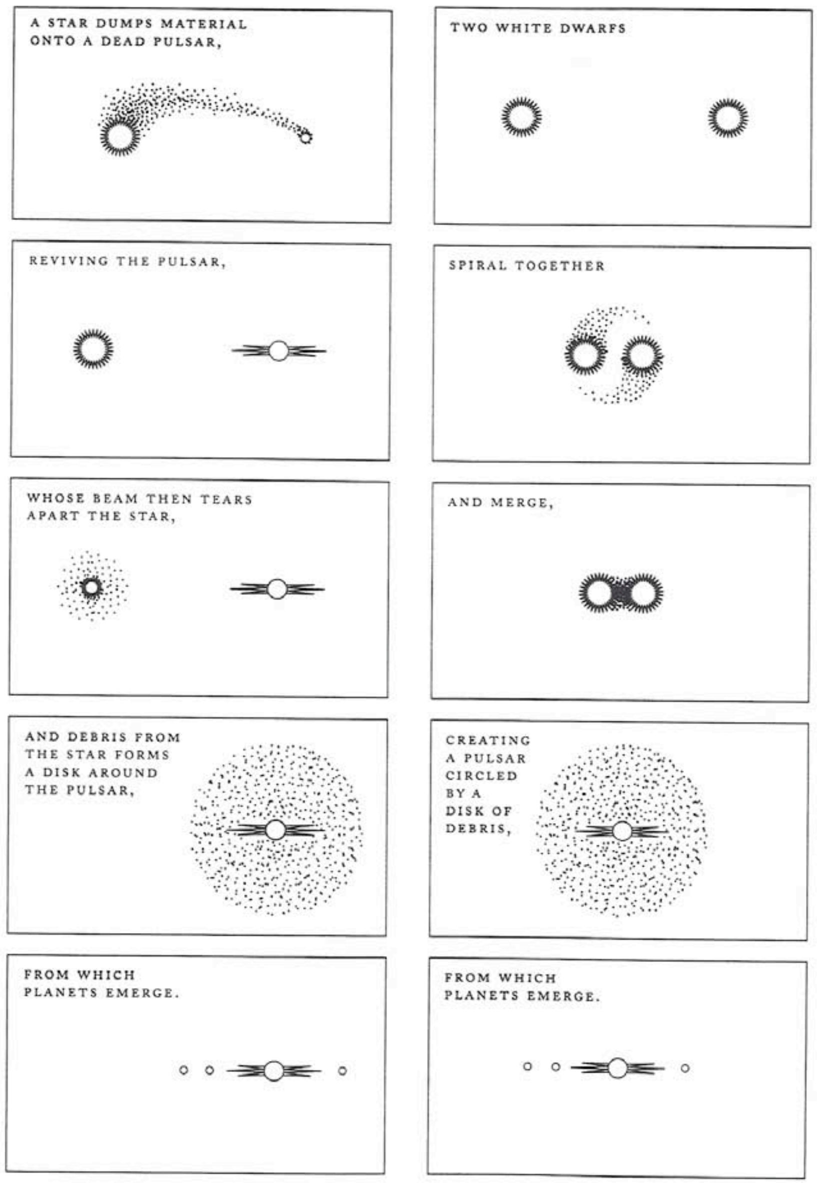
This method can detect very low mass planets, but they are one-time events. *Cannot follow up.*

OGLE 2005-BLG-235Lb, announced 1/25/06

I will not include any questions on gravitational microlensing on the exam.

Pulsar timing method

(***Not on exam***)



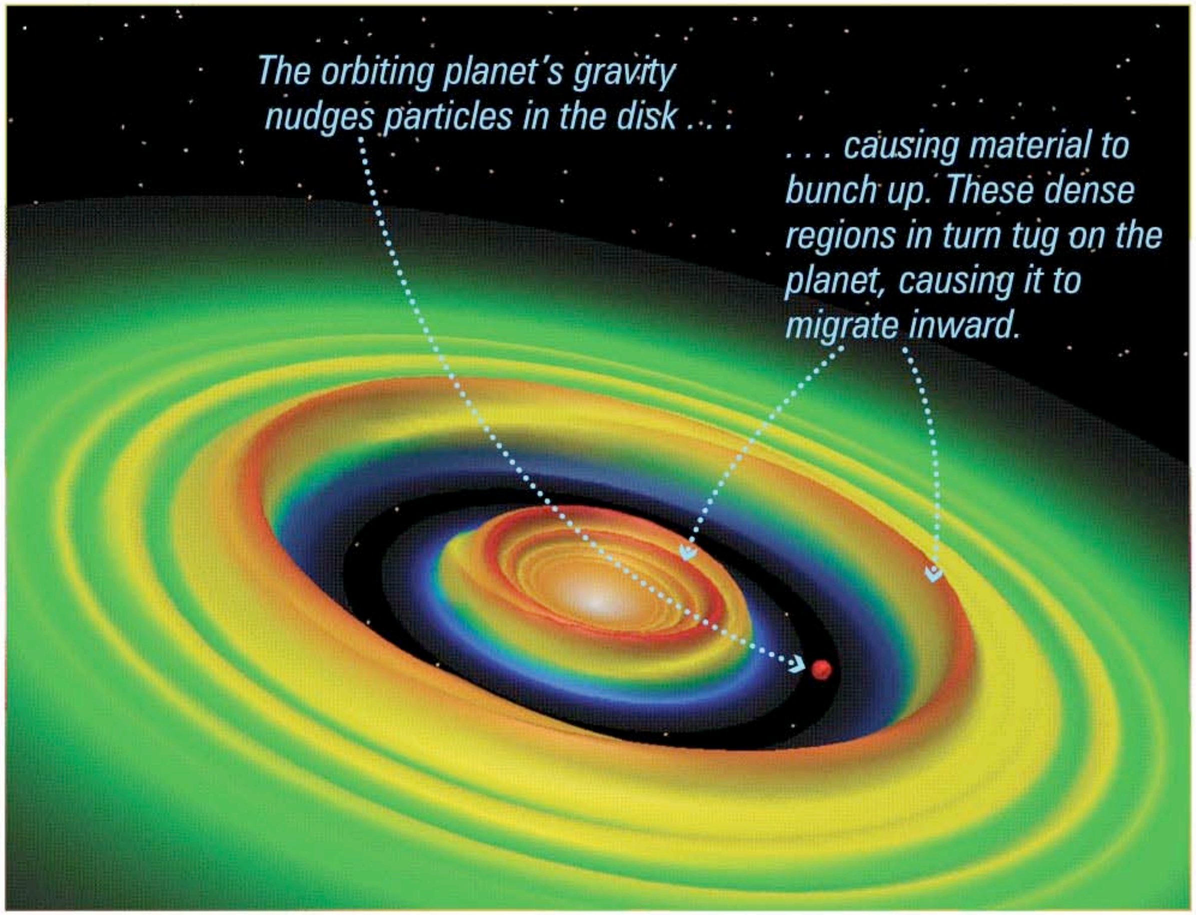
Pulsar planet production. Pulsar planets may arise when a reborn pulsar tears apart its companion star (left) or when two white dwarfs merge (right).

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

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

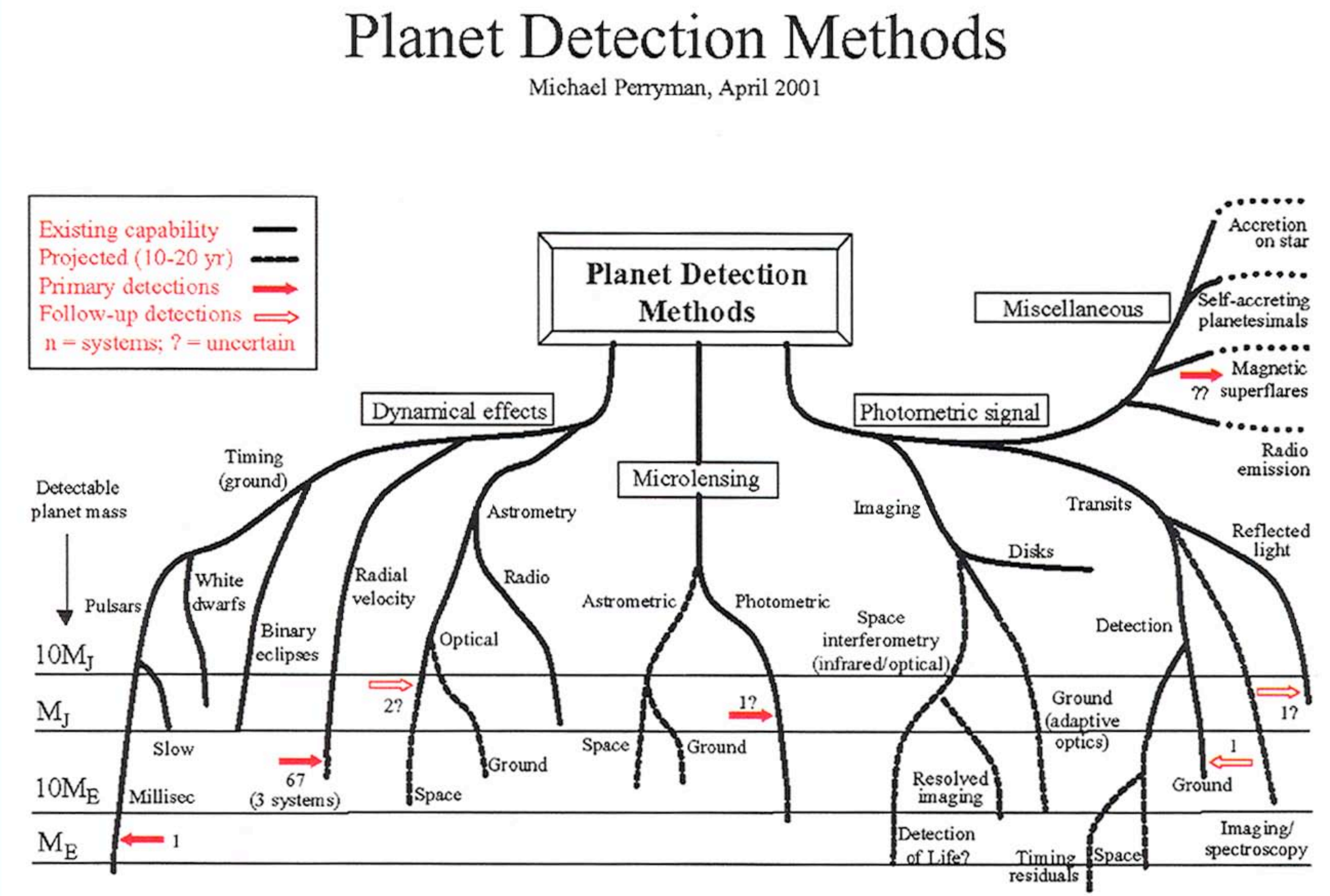
Detecting planets by their effects on disks

Notice this is the only way to detect planets *in the process of formation*.

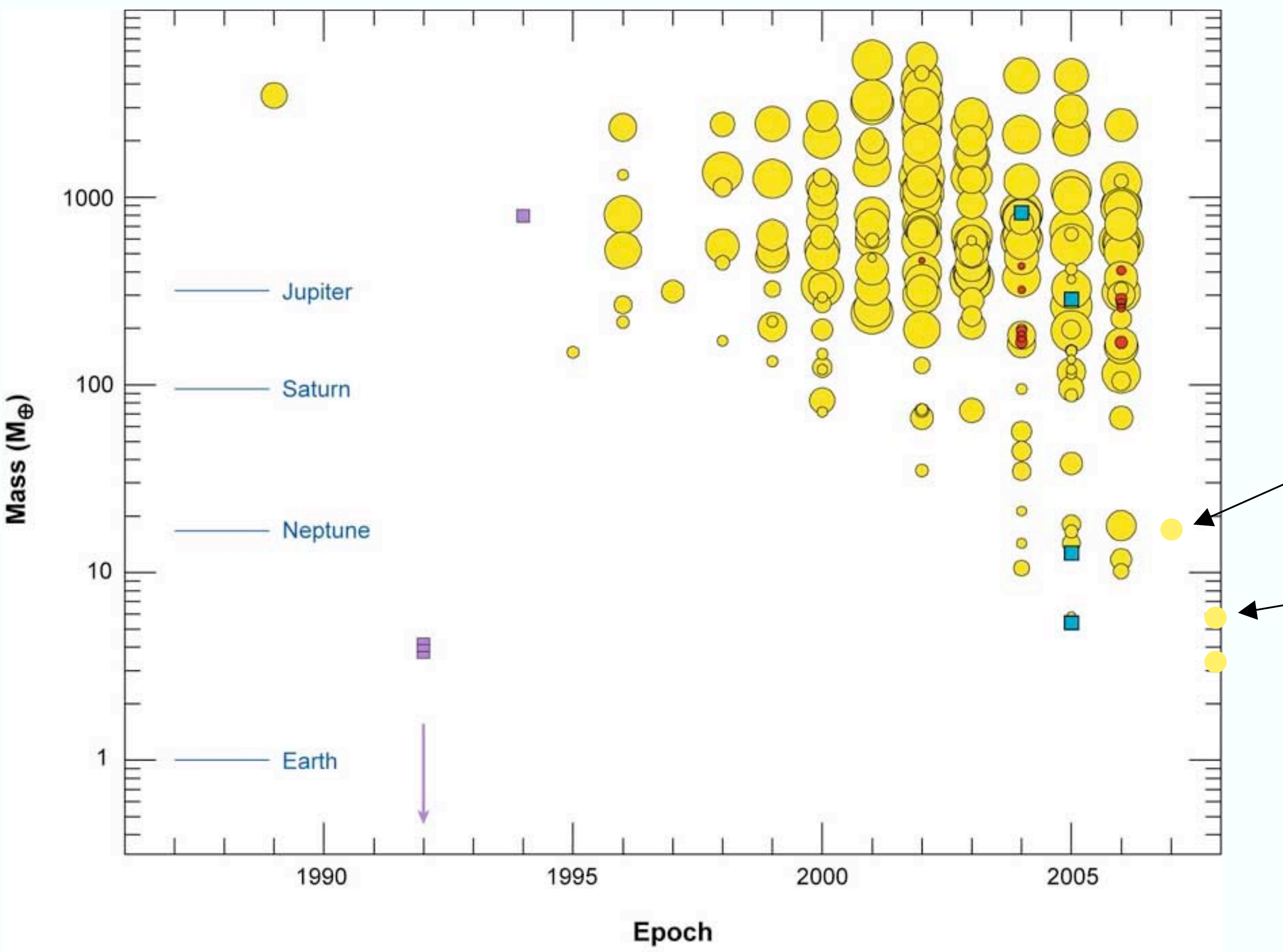


- Fig. 19 in textbook

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 have discussed only the most promising/successful methods. Still interesting to inspect this (now-famous) diagram.



With time, can detect planets of smaller and smaller mass.



Triple Neptune system

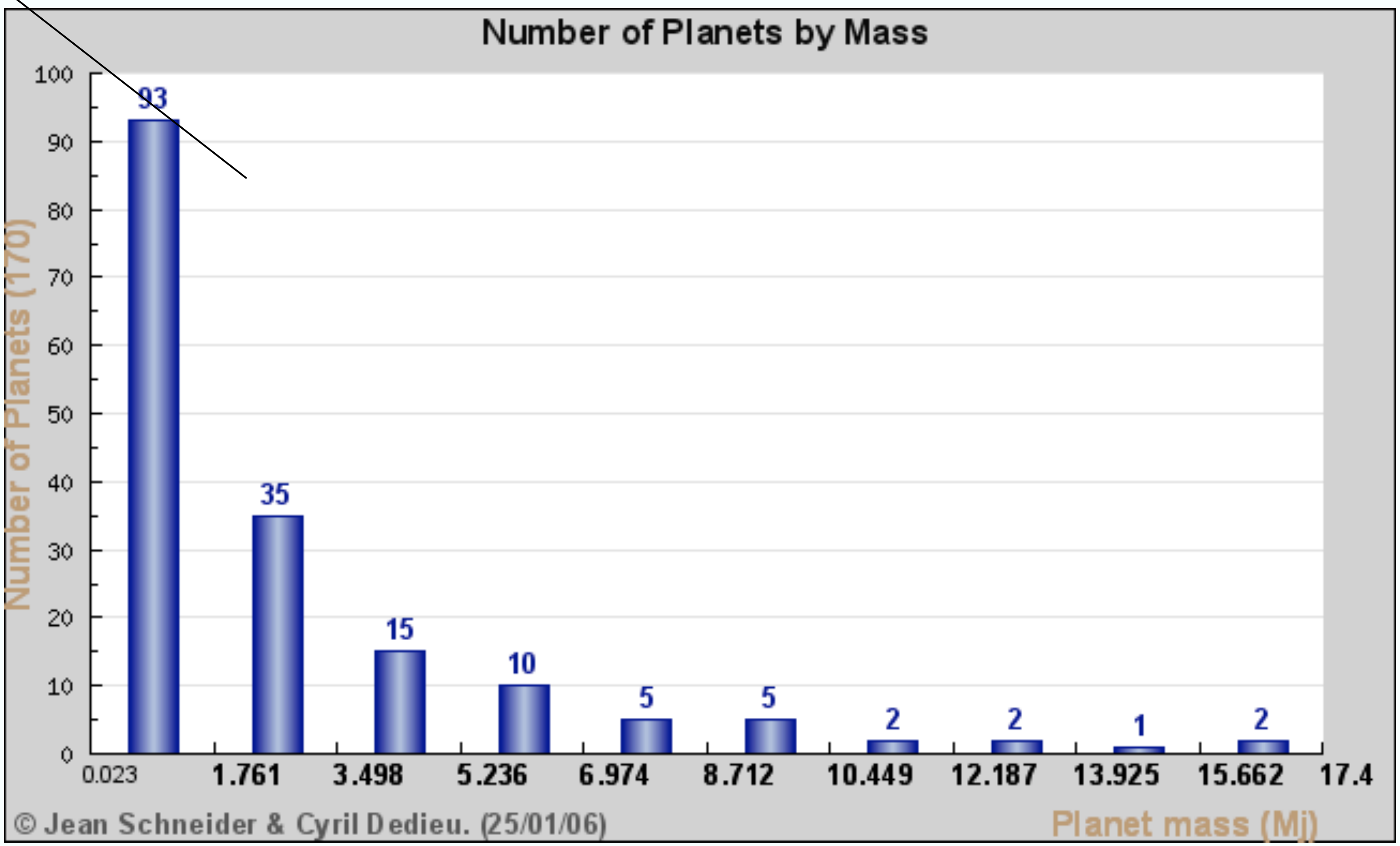
Triple Super-Earth system

There are strong indications that there are more small mass planets than large, but does it extend to terrestrial masses?

Earth-like planets?

?

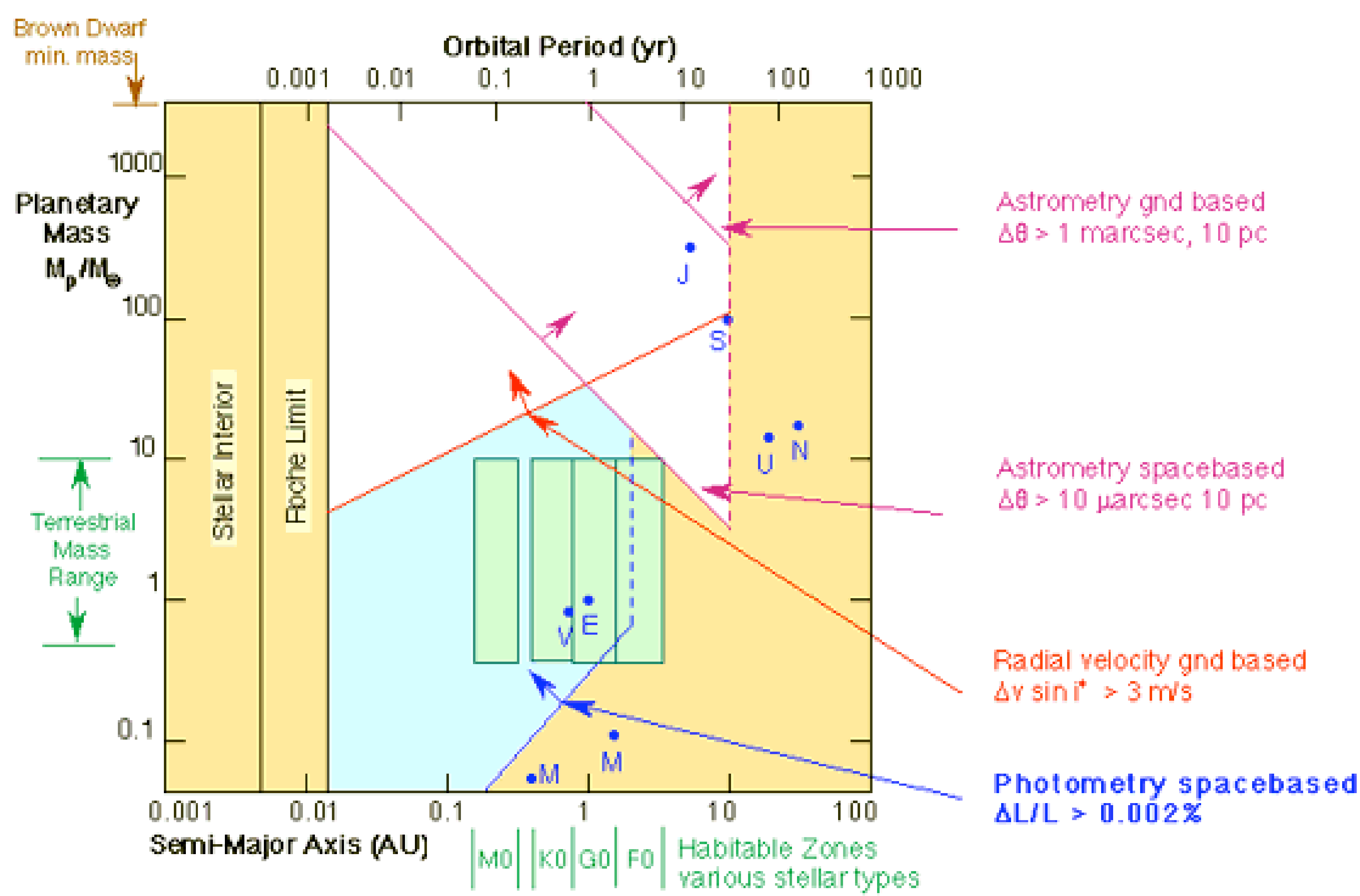
Number of planets for different masses



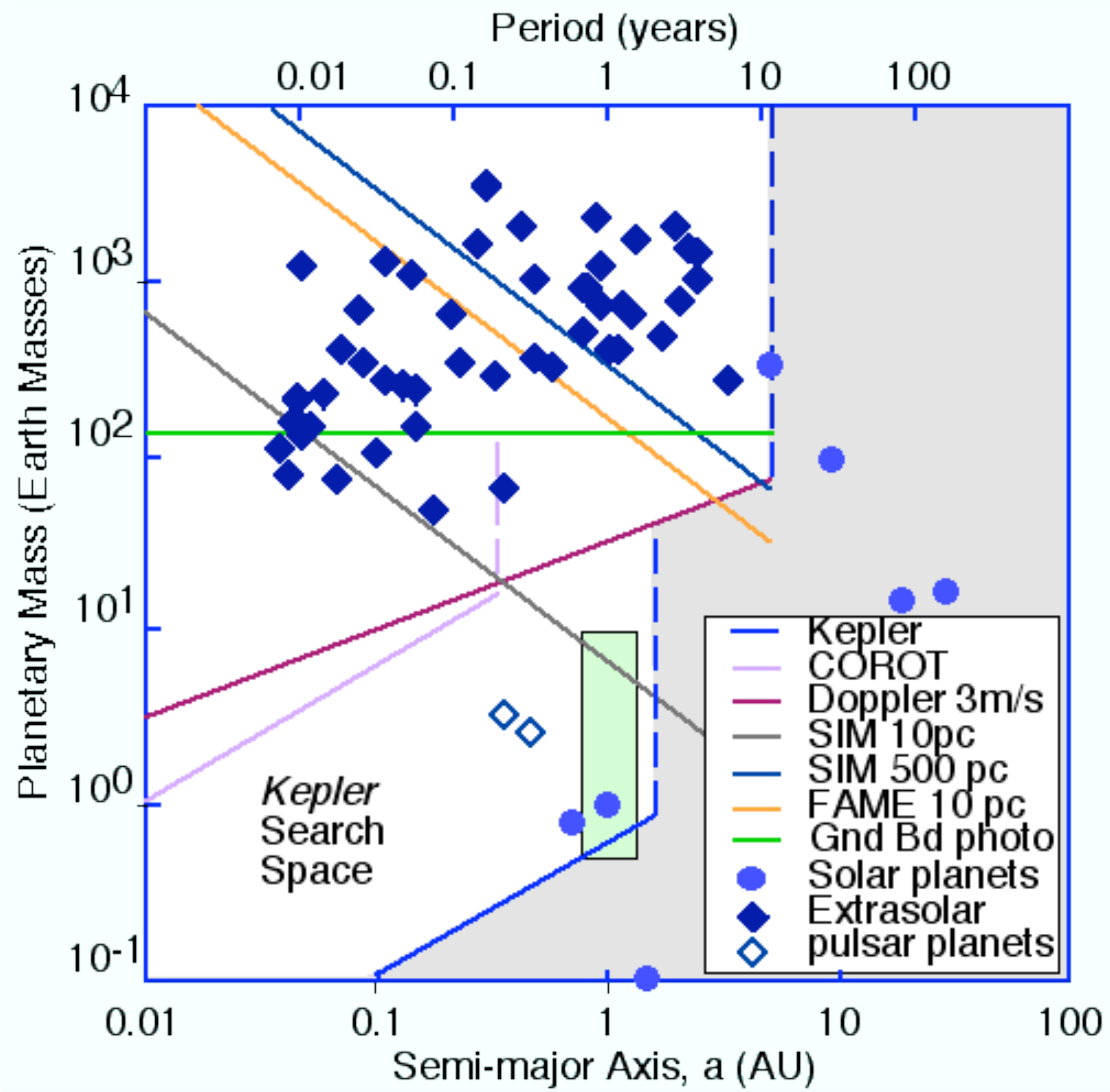
Nearly the end, but first:

Following three slides: Different versions of a diagram showing limits to different detection methods in a graph of planet mass versus planet orbital size (semimajor axis)

The following three apparently confusing diagrams contain most of the information you should know about planet detection in one place. All three are versions of the same graph, showing the various limits for different detection methods in a plot of planet mass (in Earth masses) vs. planet's orbit size (semimajor axis) in AU. Serious inspection of them, and their labels, should help you become comfortable with at least the terminology.



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 methods, you will do well on this part of the exam. (See next slide for more challenging version.)



You should be familiar with the following space-based planet detection missions:

Kepler
CoRoT
SIM
GAIA

More recent (and detailed) version of previous plot: Sept. 2007

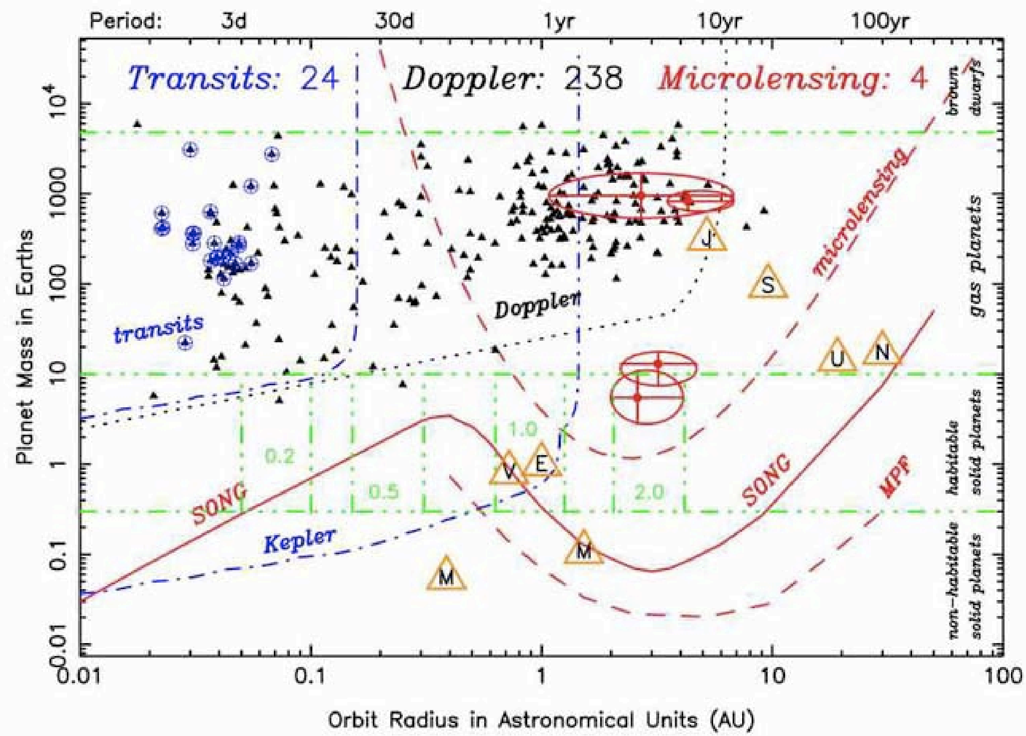


Figure 2. Mass and orbital radius of all known exoplanets as of September 2007 (indicated by black triangles, blue circles and red ellipses for Doppler, transit, and microlensing detections, respectively). Detection limits of existing ground-based observations are marked 'transits', 'Doppler' and 'microlensing'. The full drawn line marked 'SONG' is the detection limit for the combined radial velocity and microlensing network described in the text. Also shown is the sensitivity of the coming Kepler satellite, and the sensitivity that could be obtained by microlensing observations in space ('MPF'). Vertically, the diagram is divided into brown dwarfs (above 15 Jupiter-masses), gas planets (10 $M_\oplus$ to 15 $M_{\rm jup}$), habitable solid planets (0.3 $M_\oplus$ to 10 $M_\oplus$), and non-habitable solid planets (i.e. below 0.3 $M_\oplus$). The inner and outer distance where planetary surface temperature may be right for liquid water is marked for stellar masses of 0.2, 0.5, 1.0 and 2.0 $M_\odot$. The

Don't be mislead by the complexity of this plot. Just ask yourself basic questions like:

1. Why are most of the transit planets to the left of the Doppler (radial velocity) planets?

More questions are given on the following slide. These should be good review questions after you are through studying the material, because the diagram above places what you should know in a very different context than what you may have memorized.

More questions about the previous graph

2. Notice that the Doppler planets have a lower mass limit that increases as you go to larger orbital radii. Why is it more difficult to detect an extrasolar planet by the r.v. method at larger orbital radii? (This is the main selection effect that explains why most Planet detections have been made with this method.)

3. The habitable planet regions of this graph are shown as masses between 0.3 and 10 Earth masses; habitable zone orbit radii are shown as green rectangles for stars of four masses. Try to understand why it will be easiest to detect habitable zone planets orbiting *low*-mass stars, for either r.v. or transit methods.

4. Look at the limit marked "Kepler." Knowing the method to be used by the Kepler mission, explain why this mass limit curve slopes upward as it does. Why do you think there is a sudden vertical upturn at about 1 AU? Notice the relation of the Kepler curve to habitable zone planets.

5. Notice that no planned experiment would detect Mercury orbiting the Sun, and only the space-based gravitational microlensing curve ("MPF") would detect Mars.

6. The astrometric method is conspicuously missing from this diagram. Very roughly, where in this diagram would the detection limits for this method fall? (Remember the most important difference between the r.v. and astrometric methods.)