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 $\text{H} \rightarrow \text{He}$  
$M > 0.1 \text{ Msun}$  
- Luminosity comes from heating by nuclear fusion.

**Brown dwarf**: mass too small for nuclear fusion.  
$M < 0.1 \text{ Msun} \approx 80 \text{ Mjup}$  
- Luminosity from slow contraction, release of gravitational energy.  
- Probably form in similar manner as stars.

**Planet**: Upper limit usually taken as $\approx 10 - 20 \text{ MJup}$.  
Lower mass limit not too important because we couldn’t detect it. Mars counts as a planet ($0.1 \text{ Mearth}$), 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 ($\approx 20 \text{ M}_{\text{earth}}$); and (more recently) Super-Earths ($\approx 5-10 \text{ M}_{\text{earth}}$). 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?

<table>
<thead>
<tr>
<th></th>
<th>STARS</th>
<th>BROWN DWARFS</th>
<th>GIANT PLANETS</th>
<th>TERRESTRIAL-LIKE PLANETS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass (solar units)</td>
<td>O star</td>
<td>Sun</td>
<td>M star</td>
<td>(BD limit)</td>
</tr>
<tr>
<td></td>
<td>100$M_\odot$</td>
<td>...</td>
<td>...</td>
<td>0.08$M_\odot$</td>
</tr>
<tr>
<td>Mass (Jupiter units)</td>
<td>1000$M_J$</td>
<td>...</td>
<td>80$M_J$</td>
<td>...</td>
</tr>
<tr>
<td>Surface temperature</td>
<td>50,000K</td>
<td>6,000K</td>
<td>...</td>
<td>3,000K</td>
</tr>
<tr>
<td>Color</td>
<td>blue</td>
<td>yellow</td>
<td>red</td>
<td>...</td>
</tr>
<tr>
<td></td>
<td>formed from cloud collapse</td>
<td>formed from protostellar disk</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>nuclear fusion</td>
<td>gravitational heating, fading</td>
<td>light from parent star, internal radioactivity</td>
<td></td>
</tr>
<tr>
<td></td>
<td>gaseous</td>
<td>solid surface</td>
<td></td>
<td></td>
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</tbody>
</table>


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.

Direct detection: currently not feasible except for extremely massive planets.
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 principle behind several methods of exoplanet detection involves observing these orbits. 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.
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

Jupiter actually orbits the center of mass every 12 years, but appears to orbit the Sun because the center of mass is so close to the Sun.

The Sun also orbits the center of mass every 12 years.

Not to scale!

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.

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 $\rightarrow$ Resulting radial velocity curve

Also see Figures in textbook

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
Textbook version of previous figures

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

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**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

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

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**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.

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• Figs. 11, 12 in Ch. 11 of textbook.
Comparison of two search methods

Advantages

**Astrometric**
- Big Planet
- Big Orbit
- Small Star
- Nearby Star

**Spectroscopic**
- Big Planet
- Small Orbit
- Small Star
- 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!
Big surprise in 1995: Radial velocity curve of star 51 Pegasi shows large radial velocity amplitude and orbital period of \textit{days}, not years! Must be giant planet \textit{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. \textbf{Why?}
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.
The radial velocity method allows 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 $90^\circ$ 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
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.
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.

<table>
<thead>
<tr>
<th></th>
<th>Astrometry</th>
<th>Doppler</th>
</tr>
</thead>
<tbody>
<tr>
<td>Easiest planetary mass to detect?</td>
<td>Large</td>
<td>Large</td>
</tr>
<tr>
<td>Easiest planetary distance from star?</td>
<td>Large</td>
<td>Small</td>
</tr>
<tr>
<td>Easiest orbital period of planet?</td>
<td>Long</td>
<td>Short</td>
</tr>
<tr>
<td>Best distance of star from Earth?</td>
<td>Nearby</td>
<td>Irrelevant</td>
</tr>
<tr>
<td>Can mass of planet be measured?</td>
<td>Yes</td>
<td>No; only a minimum</td>
</tr>
</tbody>
</table>

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 star’s diameter and mass, and so get density. Also: can observe planet’s spectrum!

![Diagram of a transit method with labels for brightness and time, showing the light curve of a planet transiting a star.](image-url)
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*

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

**Light Curve of OGLE-2005-BLG-390**

- Sharp spike indicates second lens.
- Mass of second lens only $8 \times 10^{-5}$ as massive as star. Most likely mass of this planet is $5.5 \, M_{\text{earth}}$ and separation from star is 2.6 AU.
- Most likely star is low mass (0.22 $M_{\text{sun}}$). *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.*

*I will not include any questions on gravitational microlensing on the exam.*
Pulsar timing method

(Not on exam)

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

Earth-like planets?
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

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.)