Planet Detection Techniques and Results (outline of lectures)

These notes are meant to be read in conjunction with the lecture presentation. A pdf of the powerpoint presentation containing all the illustrations is available online, and a hardcopy version will be available at PMA.
[A list of web sites giving more details and programs can be found as a Word document at the class web site. Ch. 10.3 of our textbook gives a good, if brief, account of methods; Ch.5 of Koerner & LeVay's book (on reserves at PMA library and available online at course web site) gives a good complementary review, only a little out of date, and a few omissions. Notice that gravitational lensing and timing methods are not covered in your textbook.] The powerpoint presentation used in the lectures will be available as a pdf, and contains many illustrations that complement the abbreviated *outline* of the lectures given here.

We will work through the many methods that have been proposed or attempted (some successfully) to detect extrasolar planets. You should be able to explain each method in words, how it works, what sorts of planets it is designed to find, whether it has been successful so far and why or why not. You should also be able to summarize what we have learned from the detection of over 100 extrasolar planets so far.

1. **Center of mass wobble of parent star**: First must understand how star and planet both orbit about the center of mass (or "barycenter"), which is much closer to the star than the planet.

Favors detection of massive planets (can get "Jupiters", but won't get terrestrial planets this way) because a massive planet produces the biggest gravitational effect on the star, for all of the methods discussed elow. Three completely different approaches are used:

A. Periodic change in ***stellar*** position: called "**astrometric**" (means "measuring positions) or "angular perturbation" method.

This method has the longest history, but several false detections in past; reason is it takes *decades* to use this method (see below).

See "wavy" motion of star because center of mass is wobbling. (See fig. 10.5 in text and illustrations in ppt presentation.)

Most sensitive to distant (from parent star) planets [Understand why]⇒ long periods ⇒ have to wait many years!

Also, need astrometric (position) accuracy of *milli*-arcseconds to get "Jupiters," *micro*-arcseconds to get "Earths." For example Jupiter from 10 pc would require 0.003 arcsec resolution (see text, pp. 255-256).

To date no discoveries (one verification of r.v. method), but that is a selection effect. If there are more giant planets far from their stars, the should start showing up within a few more years.

Many programs at work from the ground: PTI (see outside reading) gets 50 micro-arcsec, Keck interferometer will get 10-30. But will need future ambitious space missions (SIM [2007?], GAIA [2010?;5 year lifetime]—hundreds of thousands of solar-like (FGK) stars will be searched to detect thousands of Jupiter-like planets, and maybe some Earth-like planets.

B. Periodic change in stellar **radial velocity** (r.v.). [see figs. 10.7-10.9 in text]

Most sensitive to planets close to parent star. [Understand why]

But only gives lower limit to masses because orbital inclination matters (think about it).

Can get orbital eccentricity (see figure in text, and explained in class).

Need to detect r.v. variation of ~10 meters/sec to see Jupiter. Can now get down to ~2-3 meters/sec (optimistic), but 1 meter/sec seems like absolute limit. So will probably *never* detect Earth-like planets this way.

But it is fantastically successful at detecting massive (Jupiter-like) planets: over 100 detected so far! [Be sure to go to the Extrasolar Planet Encyclopedia, and the other extrasolar planet sites listed at the "Astrobiology Web" at

http://www.astrobiology.com/extrasolar.html

In fact, with a few exceptions, it is the *only* method that has so far (because of its nature) been successful.

Detailed results summarized in class and in text (see pdf of ppt lecture material for many graphs). At this time there have been 147 extrasolar planets discovered in 128 planetary systems (some have more than one planet). Lots of big surprises: "hot Jupiters", large orbital eccentricities (completely unlike our solar system) in many cases. We will discuss details and implications of these results. There is at least one 3-planet system, and15 multiple planet systems now known. Planet in a binary system.

C. **Timing** methods –periodic light travel time variations in a stellar "clock". (Explained in class.)

1992: Pulsar planets discovered (from delays in the light arrival time of pulsar pulses, because pulsar's distance from us is changing. Explained in class.)

PSR 1257+12: 3 planets (now 4?); distance ratios almost identical to those of innermost 3 planets in our solar system! But how could these planets have formed?? Surely couldn't have survived the supernova that preceded the pulsar! Illustration of possible formation of a dust disk during the merger of two white dwarfs to make a pulsar will be shown in class.

According to the Extrasolar Planet Encyclopedia, a second pulsar containing a planet has been (tentatively) discovered. This one has as mass of 2.5 times Jupiter's.

Current searches: using white dwarf oscillations as clocks (UT program)

2. Photometric methods

A. Transits: Searches for signs of eclipse of star by orbiting planet (similar to how eclipsing binary stars are discovered). [See figs. 10.10, 10.11 in textbook.]

Must look for very small (< 0.1%) dip in light curve, because planet is so small compared to star.

Need nearly edge-on planetary orbit, so chances of detection are only ~1%. But if you monitor many thousands of stars… Rewards are very large: can get mass *and* size of planet as well as information about the planet's atmosphere. [In 2001 HST observed starlight filtered through a planet's atmosphere during a transit.]

With simultaneous transit and r.v. data, can get even more detailed information.

However, difficult to get such photometric accuracy. In summer 2003 the first transit discovery of an exoplanet occurred. See the STARE web page for details. Since then at least three additional transit exoplanets have been discovered (and confirmed with the radial velocity method).

Jupiters: require milli-magnitude (~ 0.1%) ⇒ can do from ground. STARE, VULCAN,… See web site "Extrasolar Planet Encyclopedia" for amazingly large list of transit projects. Earths: require <micro-magnitude ⇒ must go to space: COROT (Europe), KEPLER (U.S., approved for 2007; 10^5 stars!). Kepler will be able to detect transits that reduce star's light by only about 0.01%, so will surely detect lots more massive planets, but also (if they exist) some terrestrial-mass planets.

B. Gravitational microlensing: [As far as I can tell, this method is not even mentioned in your text or outside reading! Many people are too skeptical of it, but it has redeemed itself recently.] This method uses stars in our Galactic bulge as sources of light rays which are bent by the gravitational fields of the "lens" stars in the foreground, between us and the Galactic bulge. This gives a "microlensing light curve" that rises and falls (shown in class). Planets that orbit these "lens" stars can be detected when the light rays from one of the lensed images pass close to a planet orbiting the lens star. The gravitational field of the planet distorts the light curve: the deviation is typically about 10%, and duration is a few hours to a day (compared to 1-2 months for the lensing due to the star).

Unique advantage: Strength of signal is nearly independent of planetary mass! Microlensing signals of low-mass planets have shorter duration and lower detection probability compared to high-mass planets, but not a weaker signal. So microlensing surveys with frequent observations of *large* number of stars should be able to detect terrestrial planets with good confidence.

The big challenge is that microlensing events are rare, so have to monitor *millions* of stars, and even of those that lens, only about 2% of earth-mass planets orbiting these stars will be in right position to be detected (if all the stars have earth-mass planets). Also need very good angular resolution and fairly accurate (~1%) photometry. Several other problems, but these are being addressed.

GEST (Galactic Exoplanet Survey Telescope)—1.5m space telescope with large field of view. Will survey about 100 million stars. Could detect planets down to Mars mass, should find ~100 Earth-mass planets at 1AU (if all stars have such planets). "Free-floating" planets will also be detected! (Only method that can do that.) Will also be able to detect ~50,000 giant planets by transits. Sensitive to planets at nearly all distances from star, unlike other methods.

See if you can find the GEST program through links at one of the web sites on our class web page. What is its status? Are there other ongoing programs to discover planets using microlensing?

The ppt presentation that you will have access to will have some diagrams illustrating this technique.

3. Direct detection

By **reflected starlight**, need to see object 10^9 times fainter than star (for Jupiter size); using infrared radiation from the planet, this could be reduced to $\sim10^5$, but that is still too large for any present telescope. Graph illustrating this shown in class.

Angular resolution is another problem. A planet at 1AU from a star 10 pc away from us probably could not be resolved with present techniques (although you will be given a homework assignment about a recent development in this area).

Need "nulling interferometer" or advanced coronograph (+ excellent adaptive optics if from the ground).

There are claims that Jupiter-size planets will be directly detected from adaptive optics ground-based telescopes (Keck interferometer). But Earth-size planets are completely out of the question.

Long-term future space missions to directly image Earth-like planets and get spectra: Terrestrial Planet Finder (TPF), Darwin (Europe), Planet Imager (PI)

Spectra could give direct signature of "biomarkers", especially ozone (since shouldn't be much oxygen before photosynthetic life). Examples shown in class and in text. Will discuss in more detail in class.

Even without spectra, just photometric "light curve" (as the planet rotates) could in principle give evidence on fraction of surface covered by clouds, land mass, oceans, ice, vegetation,…, as mentioned in text [Ford et al. 2001 Nature, 412, 885] and shown in class.

We will return to this again later. For now just understand the problems with the faintness of the planet (so need some kind of coronagraph), and the need for extremely high resolution (so some kind of interferometer).

Notice that there is a very recent claim that a planet considerably more massive than Jupiter has been directly imaged orbiting a brown dwarf. Search web sites for details.

Free-floating planets (see pp. 239, 255 in text): There are also claims that "free-floating" or "rogue" planets have been detected. These would be planets without any parent star. However even the best candidate is still controversial. (You should try to find out why.) If they exist, they were almost certainly ejected from the the planetary system in which they were born. They are extremely difficult to detect unless they are very large (think: why?), and some people speculate that *most* planets might be free-floating planets! There has even been speculation (made years ago) about why such planets, if they had masses like Earth's could even be habitable (have temperatures in the right range for liquid water) even though they are in near-absolute-zero interstellar space.

Thousands of planets? More indirect argument. (Illustrations for this material was in the last part of the ppt.pdf presentation on Planet Formation Theories.)

Why does Uranus (and Pluto) spin (rotate) on its side?

Why does Neptune's moon Triton orbit its planet in “wrong” (“retrograde”) direction?

Why is Pluto's orbit around the Sun so elongated? (elliptical)

Likely explanation: large number of planetary collisions during early history of solar system involving BIG planetesimals or protoplanets in the outer solar system, which were subsequently ejected. (Some of them are still there, sitting just outside the orbit of Neptune, called the “Kuiper Belt” comets.) Notice that big planetesimal collisions are also favored to explain the existence of our moon and some of the peculiar properties of Mercury. (We already discussed this in the section on planet formation theories.)

How many BIG objects would you need?

Odds are very small to get *all* the anomalies listed above unless 100s or 1000s of “planets” size of Pluto or Charon were present in outer solar system, and probably closer in. Pluto + Charon would then be the only ``ice dwarf'' relics---the rest either incorporated into giant planets or ejected by gravitational scattering of these giant planets.

Most of these objects would now lie in the Oort Cloud, ~ a light year from Sun.

Sizes: maybe 200 miles to around 1200 miles diameter. So can't see by reflected sunlight.

But since they are so far from the star that they probably couldn’t have life (probably no atmosphere, too cold—see “habitable planets” section), so we will regard them as curiosities for now. But note that if the speculation is correct, there could be planetary systems with many more planets than our system, but maybe without a “Jupiter” to gravitationally kick them out. However in that case many of them may have just been pulverized

Also note: most of these ejected planetesimals (large and small) became the **Oort comet cloud** whose significance for the development of life on Earth will become apparent in the next part of the course (comet delivery of prebiotic molecules and maybe water, potential for mass extinctions,…).

For now, understand the potential interesting relation between the existence of giant planets in a planetary system and the kind of impact environment a habitable planet is liable to suffer. Your text has a good discussion of this. Notice that the authors ask you to consider whether more frequent giant impacts might even *accelerate* the development of complex life!

On the other hand, we have to appreciate the problem that giant planet migration would present for any habitable-zone planets. So it is not so obvious that there will be many habitable terrestrial-like planets, or habitable planets with life.