Notes 9: Extrasolar planets and Exo-biology

This is an interesting section. We have all sorts of observations and data concerning extrasolar planets (planets outside the solar system), but no evidence for exo-biology. This is also one of the most rapidly changing areas of astronomy so these notes will quickly become obsolete….

Defining a Planet

There has been quite a bit of discussion about distinguishing planets from smaller objects in the solar system, which led to the removal of Pluto from the planet club, but what about looking at things from the other end. When is a planet too big to be considered a planet and should instead be considered a star? To distinguish planets from stars we rely upon whether an object has the ability to have sustained nuclear fusion occurring in its core. Without fusion, it is a planet. But if it has fusion, then it can be a star – perhaps. The problem arises when we consider objects that don't have regular Main Sequence hydrogen fusion like the Sun, but have deuterium fusion. The criteria for deuterium fusion is much less rigorous than that for hydrogen fusion, so smaller mass objects can fuse deuterium.

Basically the following mass limits define the upper limits of planets –

- If the mass is $<0.013\ M_\odot$, it cannot fuse anything, and is a planet
- If the mass is between 0.013 and $0.075\ M_\odot$ it can fuse deuterium and should be considered a *brown dwarf.*
- If the mass is $>0.075\ M_\odot$, then it is a star.

In our solar system we have Jupiter with a mass of $0.00095\ M_\odot$ which clearly puts it in the planet club.

Since most extrasolar planets are defined in terms of Jupiter's mass, the above limits would be

- If the mass is $<14\ M_J$, it cannot fuse anything, and is a planet
- If the mass is between 14 and $79\ M_J$ it can fuse deuterium and should be considered a *brown dwarf.*
- If the mass is $>79\ M_J$, then it is a star.

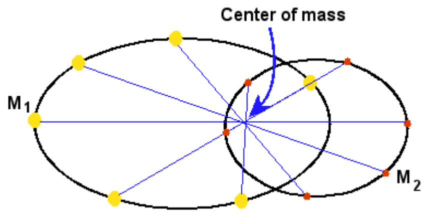
While these numbers may appear to be grounded in physics pretty firmly, it is entirely possible that planets could exist outside of the above limits, or that we may need to refine our estimates based upon new understandings of physical processes. But for now, these are the limits we'll use and now it is time to hunt for planets!

Detecting Extrasolar Planets

It has generally been viewed as impossible to directly observe a planet around another star given the relative brightness of stars relative to the amount of light reflected by a planet. Even the largest mass planets would be able to reflect a small fraction of light from the star they orbit, and the glare from stars is just too great. Also the angular size of planets makes it very difficult to detect even a wide planet.

Initial attempts to detect extrasolar planets relied upon the influence of the planet upon the star they orbit, similar to how two stars influence each other through their mutual gravity. The only problem with this method is that the influence on a star is much less than the star’s influence on the planet. For example, in our solar system, if we ignore all of the planets except for Jupiter, then you could view those two objects as being in orbit about one another. But with Jupiter having about 1000 times less mass than the Sun, it would have a minor influence on the Sun, and such a minor influence would be difficult to detect.

The influence of a massive planet on its star can be measured by how the two objects move about the center of mass (COM) of the system. Each object is technically in orbit about one another, so that each orbits about the center of mass with the same period for one orbit. There is a difference in the orbital sizes which is proportional to the masses of the two objects.



It is possible to measure from each star their average distance from the COM, which would be r_1, r_2 respectively. These values can be combined with the masses of the two objects to get the COM relationship

$$M_1 r_1 = M_2 r_2$$

The version of Kepler’s third law that we’d use for a planet-star system includes the average distances to the COM and the masses of each object, along with constants and the orbital period, P.

$$P^2 = \frac{4\pi^2 (r_1 + r_2)^3}{G(M_1 + M_2)}$$

Typically things can be simplified if P is measured in years, r_1, r_2 are measured in AU and the masses are measured in solar masses ($M_\odot$). In that case the formula becomes

$$P^2 = \frac{(r_1 + r_2)^3}{(M_1 + M_2)}$$

If you took the *Stars* course, this should be familiar.

If we use the limits that we place on planet masses, and using a mass for the star equal to the Sun, then the relative sizes of the orbits from the center of mass for the largest mass planets are

$M_1 r_1 = M_2 r_2$
$M_\odot/0.013\mathrm{M}_\odot = r_2/r_1$
$80 = r_2/r_1$

So the star is 80 times closer to the COM than the planet, which means the size of its orbit is pretty small. For a planet at a distance of 1AU from its 1 $M_{\odot}$ star, the star would be less than 3 solar radii from the COM. Given such a small size orbit, any motion in the star would be very small.

In the 1990's several groups of astronomers believed that the technology had advanced to such a level that even such small motions in a star could be observed if they used the best spectroscopes to measure minute Doppler shifts in the spectra of these stars.

But here's where things got strange. Before any of these astronomers could find a planet around a star using this method, they were scooped! In 1992, a group of entirely different astronomers noticed that a pulsar (a rotating neutron star) had orbital motion which would come from 3 planets in orbit about the pulsar. The pulsar study was helped by the fact that the radio pulses are very precise and fluctuations in the pulses caused by even small orbital motions are easier to detect than the motions of stars in small low velocity orbits about their COM. So the first planets discovered outside of the solar system were found around a dead star! These were known as PSR 1257+12b, c and d.

A note about how we name extrasolar planets. Names are given in terms of the star name similar to how we label binary stars, with the star given the designation of "a" and other things in orbit about it labeled "b", "c", "d" and so on. So if Polaris had 2 planets around it, they would be Polaris b and Polaris c. It gets confusing if the system is a binary or multiple star system, such that a companion star around Polaris would be called Polaris B. So if you got that all cleared up, we can go back to the discovery of extrasolar planets.

Eventually the first planet was discovered around a "normal" star using the small velocity motion of the star about the COM of the system. This was in 1995, with the discovery of 51 Pegasi b. Since then, over 500 extrasolar planets have been detected mainly through the minute motion of the star around the COM.

A planet's mass can be found if the motion of the star is measured and the velocity range (amplitude) is calculated using the following relation

$$Amplitude = \left(\frac{2\pi G}{P}\right)^{1/3} \frac{M_p \sin i}{(M_* + M_p)^{2/3}} \frac{1}{\sqrt{1-e^2}}$$

Where
G=gravitational constant
P=orbital period (seconds)
M_p=mass of the planet (kg)
M_*=mass of the star (kg)
i=inclination of the orbit to our line of sight (90°=edge on to our line of sight)
e=eccentricity of the orbit

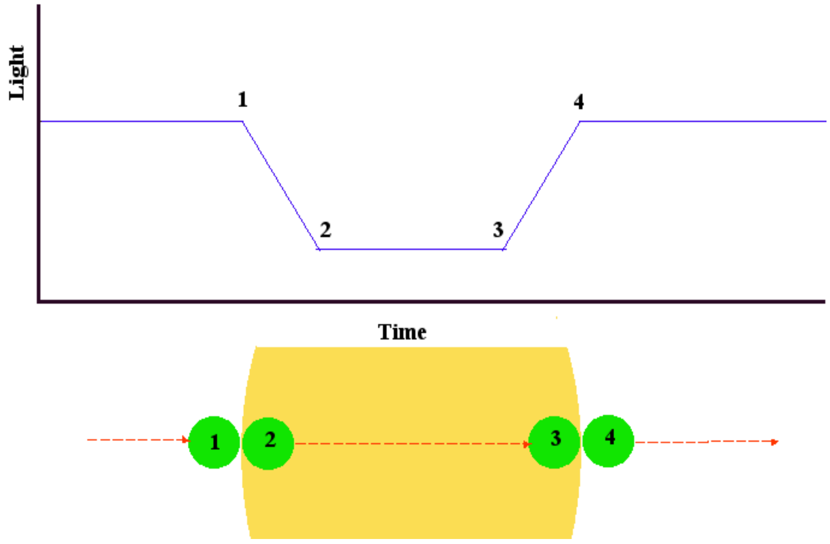
The mass of the star can be determined based upon the spectral type of the star, and the eccentricity and inclination of the orbit may be estimated based upon the variation of the velocity of the star, which would be measured in m/s (not km/s). Current studies have precise observations of stars to an accuracy of a few m/s.

Another method that has been recently used to observe planets is to look for *transits* of the planets in front of their host stars which would cause a decrease in the star's brightness. This is a very difficult thing to measure since the amount of light that is obscured by a planet is a small fraction of the overall energy output of a star. A few previously discovered planets were later found to be transiting their stars and the resulting change in brightness was a few hundredths (1/100) of a magnitude. Such observations are possible on the Earth, so long as the star doesn't have any other brightness variations (like pulsation or spots).

In 2009, the *Kepler* spacecraft was launched to search for stars with transiting planets. The precision of *Kepler's* equipment is much greater than that of an Earth-based telescope. *Kepler* has a 1.4 meter mirror and over 40 CCD chips to measure the brightness of over 140,000 stars continuously looking for the smallest changes in brightness. How small? Original design specifications were looking for variations in brightness on the order of 20 parts per million (ppm), though actual accuracy is *only* around 40 ppm. Still that is much better than most Earth-based systems.

In February 2011 it was announced that *Kepler* had possibly discovered over 1200 possible planets in nearly 1000 planetary system (further checking is required to verify these). Around one star, Kepler-11, a total of 6 planets were found with masses much less than Jupiters (down to 0.02 M_J), and orbits as close as 0.5 AU from the G type star. The large number of discoveries and the number of discoveries around planets' *Habitable Zone* extended the likely number of planets in the galaxy.

The transit method has the added advantage of possibly providing an estimate for the radii of the planets. If this information can be combined with mass information from the COM calculations, then the density of the planet can be determined. During a transit the light from the star drops fur a duration that depends upon diameter of the planet – this is shown in the illustration below.



The planet will travel from location 1 to 2 over a certain time span. The distance between 1 and 2 is equal to the diameter of the planet. And of course the distance between locations 3 and 4 is also the diameter of the planet. So long as the velocity of the planet can be measured (if you know its orbital characteristics), then that information can be combined with the transit times to determine the diameter of the planet, and estimate the density.

Another method used to find planets was actually not really looking for planets but for dark matter. *Microlensing* occurs when a small mass passes between a star and an observer, and the gravitational field of the object concentrates the light of the star so that it appears to peak sharply. This idea was proposed as a way to find low mass objects in the halo of the Milky Way, which may make up a large fraction of the dark matter thought to exist out there.

The detection of planets that may microlense the light of a distant star has resulted in the discovery of only a few planets (about 12), but such searches has also provided a great deal of information about other stars.

A few planet candidates have also been found by direct imaging, but most of these are quite uncertain.

Habitable Zone

The discovery of planets is the first step in looking for life. The next step is to determine if those planets are in a location that would support life. Such a region is defined at the *Habitable Zone.* Basically this is the area around a star where a planetary object could have water in a liquid form on its surface. The size of this region depends upon the star that it orbits and how luminous it is. But even if the habitable zone is large, it is possible that a planet could be found within it that has no atmosphere, and therefore would not likely have liquid water on its surface.

Generally speaking we scale this based upon the star's luminosity (L_*) relative to the Sun's luminosity ($L_\odot$). An approximation to the range of the habitable zone would be the following –

Inner radius = $0.7 \times (L_*/L_\odot)^{1/2}$
Outer radius = $1.5 \times (L_*/L_\odot)^{1/2}$

These relations are really just approximations, but they do give relatively good results.

Extreme Life

The limitations of life on the Earth have been expanded quite a bit with the discovery of some rather extreme life forms. Generally speaking before the 21st century, areas of the Earth with extremely high or low temperatures were considered the limits of life forms, but even in those conditions life forms thrive. But such locations on the surface of the Earth are still benefiting from the protective layer of ozone, and a nitrogen-oxygen rich atmosphere. Such conditions are not found on other worlds in the solar system, so how rigorous is life?

Apparently it is pretty rigorous. First of all we have the detection of amino acids in meteorites. While these are not life forms, they are important components involved in the development of life. If it is possible for amino acids to form in the extreme conditions within asteroids, then life forms should be found on other worlds.

On the Earth we have some very extreme life forms which include the following –

- Thermophilic (heat loving) organisms thrive in locations like hot springs, and other volcanically heated areas.
- Endolithic organisms are found inside of rocks, including in cliffs and within fossils
- Bacteria preserved in amber – this reminds one of *Jurassic Park*, but in this case, it is true that bacteria encased in amber has been retrieved, even after millions of years. In a rather unusual case of turning a profit out of this, one researcher has taken some of the ancient fungi (yeast) and has used it to brew beer. Really.
- Do we really need water? Perhaps not. Life has been detected in the driest places on Earth, such as the Atacama Desert (Chile) and Antarctica.
- Do we really need an ozone layer? What about protection from cosmic rays? Various organisms are currently being tested on the international space station and labs to determine how well they hold up in high energy environments.
- What about entirely dark environments? No problem. Lots of life forms have been found in caves and in the Earth's crust that are in complete darkness.
- Microbes on spacecraft have been found to survive long exposures to space, so even in the near vacuum of space, life can exist.
- Deep sea exploration has found a wide variety of organisms around hydrothermal vents at the bottom of the ocean, under conditions of extreme pressure, and high temperatures (remind you of a planet?).

With such discoveries on the Earth, we cannot limit ourselves to life that you are most familiar with. Odds are any organisms found on Mars today will likely be in that form – organisms, but what about in the warm oceans under the ice of Europa? Or around the vents of Enceladus? Anything is possible it seems…

Drake Equation

The search for extraterrestrial life has been a long term venture, and with the increase in technological innovations and our understanding of the universe, there have been several times that serious thought has been put forward about how many other planets may have not only life, but also life that could communicate with us. This is a very specific designation – we aren't just referring to pond scum or small microbes, but life forms that can send and receive signals across the vast reaches of space.

Frank Drake proposed the following formula to estimate the number of such civilizations across the galaxy. It makes since to limit the search to the galaxy since signals sent outside the galaxy would take millions of years to travel to other galaxies.

$$N = R_* \text{ x } f_p \text{ x } n_e \text{ x } f_l \text{ x } f_i \text{ x } f_c \text{ x } L$$

Where
N= number of communicating civilizations in the galaxy (can send signals across space)
R_*= rate at which stars form in the galaxy (stars per year)
f_p = fraction of stars with planets around them
n_e = number of planets that have appropriate environments (in Habitable Zone)
f_l = fraction of that number of planets which have life developing on them
f_i = fraction of that previous number which have intelligent life
f_c = fraction of that previous number which have the technology to communicate
L= length of time (years) which the advanced civilization has been able to send out signals into space.

Each of these items has a range of possible values, some are based on our current understanding of the galaxy and planetary science, some based upon opinions.

For example, the rate at which stars form in our galaxy is strongly dependent upon our ability to detect such events. Values for R_* range between 5-20 stars/year.

How many stars have planets around them? Again, we can make estimates based upon our ability to detect planets, but that is something we are currently only scratching the surface. Estimates can range from 1/3 to 2/3 of all stars have planets.

And of course just because you have a planet doesn't mean it is in a "good" location for life to develop. With varying sizes of habitable zones around different stellar types, there may not be an easy way to estimate this. Maybe only 1 planet per system is in the habitable zone, maybe less.

And even though you have a planet in the habitable zone, you may not have life on it. Planets like Venus and Mars are currently not very pleasant places which we think do not have life, yet they are located in our sun's habitable zone.

And even if you have life, what are the chances that life will develop to the point that it can communicate? Looking at the history of life on the Earth, we have had life on this planet for at least 2 billion years, yet only in the last 150 years have we had the ability to send signals into space. That's a lot of time when we were not very chatty. Also I think the jury is still out as to whether we have developed any intelligence on this planet……..

And the longer the communication has been going on, the greater the chance that it can be detected by others. Considering that our ability to communicate across vast stretches of space and our ability to destroy civilization are about equal, it may make this last times estimate very difficult to estimate.

Estimates for the value of N range from 1 (we are the only civilization) to many more. But since such calculations are based upon assumptions and quite a bit of guess work doesn't make them valid estimates. But one has to wonder where everyone else is….