Extrasolar Planets

Thus far we have concentrated on our own Solar System. This is a natural starting spot. But what if planets are exceedingly rare? This would put a damper on the prospects for abundant life in the universe. We therefore need information about how common planets are, and the properties of their orbits and of the planets themselves. The distances involved, however, make this challenging. Indeed, the first planets outside our Solar System were not discovered until 1992, and the first extrasolar planets around a normal star were not seen until 1995.

In this lecture we shall discuss many aspects of extrasolar planets. We will begin by considering how one detects them at all. We will then point out that the available detection techniques are strongly biased; in fact, we do not yet have the technology to detect an Earthlike planet around a Sunlike star. We will then discuss the systems we have detected, including the rather surprising revelation that most systems are radically different from our own. We will finish by discussing some of the future missions aimed at planet detection.

Detection of extrasolar planets

One's first thought might be that detection is straightforward: just observe a system with a telescope, and look for planets. The difficulty with this approach is twofold. First, stars are extremely far away. The closest one to the Sun is about 260,000 times farther away than the Earth is. At that distance, an Earth-Sun radius would subtend just 0.8 arcseconds, which is the angle spanned by the head of a pin at half a kilometer. The stars of interest are typically at least tens of times farther away from us, putting this beyond the reach of almost all current day telescopes.

The second problem is that stars are vastly brighter than planets. Recalling that planets shine by reflected light instead of by their own energy, the Earth would appear about a billion times dimmer than the Sun. Therefore, even if you could angularly resolve the systems, the poor planet would be drowned out. The ingenuity of instrument designers is impressive, though, and there are plans for future instruments that will try to get around this by holding up disks to block out the stellar light, or by using devices called interferometers to have such exceptional angular resolution that the stellar spill-over can be minimized.

In current observations, though, we have to try other methods. A different possibility might occur to you for systems that are specially oriented. If, from our viewpoint, the planet happens to orbit so that it crosses in front of, then behind, the star then we have an example of a (very) partial eclipse. For instance, the Earth has a radius roughly 1/100 of the Sun's, so it would block out $(1/100)^2 = 10^{-4}$ of the light. If the star were close enough and bright enough we might be able to measure this dip in intensity. With enough orbits we would be able to establish that this was periodic and not merely the result of sunspots or natural variation in light. This method really has resulted in planetary detections, but not many because it requires a particular orientation that is uncommon.

The method that has been used to discover almost all of the more than 300 extrasolar planets involves the Doppler shift. This is an effect that is familiar to anyone who has heard a siren approach then recede. The pitch appears to be high when the source of the noise approaches us, then appears to be low when it recedes. The same thing happens to light. When the source is coming towards us, the frequency increases. For example, light that is red in the rest frame of the source could appear green or blue. The opposite would happen if the source was moving away from us.

The key to the detection of planets is that the shift is greater for greater relative speed. In addition, because gravity is universal and mutual, a planet pulls on its host star as well as the other way around. The force is the same either way but the star's inertia is much greater than the planet's, meaning that while the planet moves at great speed in a large orbit the star is moving in a tiny circle and rather slowly. For example, consider the Earth-Sun system. Earth is moving in a 1 AU radius orbit at about 30 km s^{-1}. The Sun is 300,000 times more massive than the Earth, so it moves in an orbit that is only about 500 km in radius, and at only 10 cm s^{-1}. Not much!

That kind of speed is still undetectable around ordinary stars. However, the Sun's motion in response to Jupiter is a hefty 4.5 meters per second, and that *is* measurable (albeit with a lot of cleverness in the observational setup!). However, this detection method means that it is a lot easier to discover some types of planets than others. This is called a selection effect. Selection effects bedevil astronomy in many ways, so we need to understand them a bit before we can properly appreciate the context of the planets that have been discovered.

Selection effects

A selection effect is anything that makes it easier to observe one category of thing than another. It isn't limited to astronomy, either. There was a famous case of selection bias during the presidential election of 1936. Literary Digest, a well-known magazine with millions of subscribers, polled a list of 10 million car and phone owners about their presidential preferences, and got 2.3 million responses. Based on this massive sample, they confidently projected that Alf Landon was going to be the next president. They were very surprised when Franklin Delano Roosevelt wiped the floor with him in one of the most lopsided elections ever, but in retrospect they should have understood that their readership was fairly wealthy and thus not at all representative. Incidentally, the election was called correctly by young George Gallop, who used the technique of "stratified random sampling" of only 50,000 voters, by which a much smaller sample of representative voters gave a better idea of the tendencies of the population as a whole.

In astronomy we have lots of such problems. For example, pretty obviously, bright things are easier to see than dim things. In particular, they can be seen farther away. Without realizing this you might draw the conclusion that most stars are brighter than the Sun, because a simple count of the stars you can see with your naked eye indicates that this is the case. However, the much more numerous low-mass stars are so dim that you can't see them far away.

When it comes to planet detection using Doppler shifts, the issue is that large shifts are easier to detect. On top of that, it is much easier to be confident of your detection if you have many orbital periods. One cycle isn't enough to be sure that something else isn't going on, but ten regular cycles is plenty.

Combined, these effects mean that Doppler shifts are hugely skewed towards those coming from high-mass planets that orbit close to their host star. There are also some much more subtle effects. The Doppler shifts are established by noting the shifts in spectral lines. Therefore, stars that have more lines are more likely to allow planetary discoveries. Since the lines are associated with heavy elements (e.g., iron or titanium), stars with more heavy elements are more likely to have planets *discovered* around them, even if *in reality* they are no more likely to have planets around them. Keep these caveats in mind as we discuss the discoveries.

The first extrasolar planets

I am very pleased to report that the first accepted extrasolar planets were *not* discovered around an ordinary star like our Sun. Instead, their host star was a neutron star, one of my favorite objects. Neutron stars pack maybe 50% more mass than our Sun into a region that would fit inside the Capital Beltway: just 10 km in radius. They are formed from the collapsed cores of stars that begin their lives with at least eight times the mass of our Sun. Neutron stars often spin rapidly and have strong magnetic fields, with the result that they send out beams of radio waves and are called pulsars. These stars maintain their spin frequencies with incredible precision, and over short times they are a million times better clocks than the best clocks on Earth.

This high precision means that even a tiny tug from a planet is easily detectable. In fact, the pulsar in question, PSR 1257+12, has the three lowest-mass planets ever detected outside our solar system. Two of them have about 3-4 times the mass of the Earth, and one has about the mass of our Moon! These systems seem rare, though; the only other pulsar with a planet is a system in a globular cluster that probably got the planet though complicated pilfering from another object.

After this discovery in 1992, interest naturally turned to systems around ordinary stars. In 1995, they found one. Michel Mayor and Didier Queloz discovered that the otherwise anonymous star 51 Pegasi had a planet half the mass of Jupiter... and had an orbital period of four days!!! Mercury, the closest planet to our Sun, has an orbital period of 88 days, so the 51 Peg planet is ridiculously close. There was some skepticism initially, because models of planetary formation based on our Solar System seemed to indicate that such a system was impossible. However, with such a short period and such large Doppler shifts this discovery was confirmed quickly.

At that point the race was on. As of October 30, 2009, 403 extrasolar planets had been discovered (for an indication of the pace of discovery, a year ago there were 313 known!). There are 45 multiple-planet systems (20 were known a year ago), with the current record holder (the system around 55 Cancri) having five planets so far detected. We will now consider the properties of these systems compared to our Solar System, and what this might tell us about the prospects for life.

Properties of extrasolar planet systems

Let's first remind ourselves of the properties of our Solar System. We have eight official planets (ever since Pluto was demoted). The closest planet, Mercury, has an orbital period of 88 days. The next ones are Venus and the Earth, with orbital periods of respectively 225 days and 365 days. The only planets with large mass are very far away, with orbital periods of many years. The eccentricities of the orbits are also small. Mercury has the highest eccentricity, $e = 0.21$, but none of the others have eccentricities greater than $e = 0.09$ (Mars), and two planets (Venus and Neptune) have eccentricities less than 0.01. All of their orbits, even Mercury's, look like circles to the naked eye; if you viewed Mercury's orbit it would appear to be a circle in which the Sun was somewhat offset from the center.

The first surprise is how many planets there are with extremely short periods. Of the 403 planets, 15 have orbital periods less than two days! Another 54 have orbital periods between two and four days. These are amazingly small. In fact, they are so close that the tides they raise on their host stars are probably bringing the planets *closer* with time. That is, the stars are probably rotating more slowly than the planets orbit, so the tidal bulge lags the planet and takes angular momentum away from it. The time for inspiral, however, is many billions of years.

The second surprise is that these very close-in planets are *big*. For example, all but one of the 15 with periods less than two days have masses greater than Jupiter. Doesn't this completely contradict what we said earlier in class, that big planets could only form beyond the frost line? Oddly enough, there is no contradiction. We still have strong reasons to believe that large planets can only *form* far enough away that ices can condense. However, these planets can drift inwards. They could do this by being dragged along as the disk of gas around the star moves towards the star. The currently unresolved question is what would *stop* them from drifting all the way to the star itself. Does something naturally stop them?

Or could it be that many other high-mass planets were dragged in, and we only see the last one or few, which survived because by that time there was very little mass left in the disk and thus the dragging was ineffective?

The close-in planets all have very small or unmeasurable eccentricities, which is expected from the effects of tidal forces. The more distant ones, though, are a different story. 42 of the 403 have eccentricities greater than 0.5, which really would look elliptical to your eyes. Three have eccentricities more than 0.9! Remarkably, this is a lot more consistent with numerical simulations of planet formation than our Solar System is. The reason is that towards the end, when there are just a few large protoplanets around, their mutual gravity tends to perturb each other, leading to higher eccentricities. Could it be that the relatively small eccentricities in our system are favorable to or even essential for life?

Lessons

Let us now think about these properties in light of the selection effects we discussed earlier. High-mass, short-period planets are much easier to detect than low-mass or long-period planets. None of the terrestrial planets (Mercury through Mars) could be seen, for example. It is therefore not surprising that we have this bias. As the time of observation has lengthened, so has the maximum orbital period of detected planets. We have even detected what is basically a clone of Jupiter: 0.947 Jupiter masses, orbital radius of 4.2 AU (Jupiter is at 5.2 AU), and eccentricity of 0.044 (Jupiter's is 0.048). However, Saturn, Uranus, and Neptune would not be currently detectable because their orbital periods are longer than we have been looking with sufficient precision. We can therefore safely assume that many of the systems that have only one known planet really have a lot more.

Even with that, some 5% of Sun-type stars that have been examined have detected planets, and the fraction is going up. There are also some low-mass stars with planets, but these have been searched less thoroughly because we are interested in systems like ours. This fraction is high enough that planets really do appear pretty common. There might be a bias towards a higher probability of planets in stellar systems with more heavy elements, but as we discussed earlier this could in part be because such stars have more spectral lines and thus discovery is easier.

Our inability to detect Earth-mass planets around normal stars means that there is lingering uncertainty about how common they are. In systems with "hot Jupiters" (with small orbital periods), it is thought that the process of moving in from the much larger formation radius would have kicked out any embryonic terrestrials in the way. In addition, systems with high-eccentricity orbits for its giant planets would likely eject anything between closest and farthest approach. By these criteria, most of the currently discovered systems could not host an Earth-mass planet within the habitable zone. This may not be such a big problem, however, because much futher observation must be done before we can rule out the possibility that large numbers of such systems exist. In addition, as we mentioned with Europa, it may be that moons of giant planets are excellent candidates to host life.

The interest in extrasolar life has exploded, and there are many additional detection methods and planned missions. One example has to do with a cool effect called microlensing. The path of a light ray is bent by gravity. Therefore, light from a distant star can be deflected by a star in the way. If that “lens” star has a planet, the light that we see varies in a characteristic way. This has been used to detect several planets, and efforts are underway to increase the number with enhanced sensitivity.

Another method is to track the location of the star very carefully. We have emphasized Doppler shifts, but these only tell us the component of the stellar motion towards or away from us. If we had sufficiently good information about the apparent location of the star, we could see it moving in tiny circles on the sky. Indeed, this was how the very dim companion to Sirius (the brightest star in the sky) was first suspected in 1844. The technology for this is in development, and is likely to be productive within several years.

In the meantime, other firsts have been achieved. Perhaps the most exciting is that a year ago we had a report of the spectrum of an extrasolar planet. This was possible because a close-in planet had an orbit that crossed the star from our point of view, so it was possible to see absorption lines that indicated silicate clouds. More instances of this will occur with time, although with current technology it is unlikely that we will get much more detail.

In summary, in your lifetimes we have gone from not knowing of any planets outside of the Solar System to having a vast and rapidly-expanding set of exoplanets. This tells us that planets are very common indeed. What we don’t know, and what you can think about, is whether planets suitable for life are also common or whether we are very unusual in that respect.