Exoplanets

by Uriel A. Goldvais

Planet Earth, our home, is one of the eight planets that orbit the Sun, an average star, one of 200 billions in the Milky Way. With so many stars in the galaxy, what are the odds that the Sun is the only star containing a system of planets?

This question received an answer on October 6th, 1995: the first planet orbiting another star was found. Before that, some planets were found orbiting pulsars, but I will not discuss this kind of systems in this document.

To date, more than 200 planets have been found orbiting other stars. The technology used to discover these planets has advanced so much in the last decade that, in average, there is almost one discovery per week.

There are two main goals in searching for exoplanets. The first, related to planet formation around stars. All the theories we had were based on our own Solar System, and on observations of protoplanetary disks around other stars: disks of dust and gas that orbit around a star, from which planets are formed. After the first exoplanets were discovered, astronomers started to believe that the theories were not right or not complete: most of the planets found were as big and as massive as Jupiter (or even bigger), orbiting their parent start at the distance Mercury orbits the Sun. None of the planet formation theories could explain that. From those findings, new theories were formulated (e.g. planet migration). The second goal is related to answering one of the oldest questions of all: are we alone in the universe? By finding planets like the Earth, in the habitable zone[1] of other stars, we can find proof that life may (and probably does) exist on other places.

Finding Exoplanets

The planets in our Solar system were discovered by a method called direct detection: astronomers looked at objects in the sky that appeared to move against background stars, and, by studying this movement, they understood that these objects orbit the Sun as Earth does and therefore, they are also planets. But planets are not sources of light: they only reflect a small part of their parent star's light. When searching for exoplanets, if they are present, they will be so close to the star (i.e. small angular separation), and so dim (with respect to the star), that they become invisible (in visible light[2]). Therefore, direct detection of exoplanets is almost impossible, and other methods are used to find them. Each one of these methods has its own pros, cons, limits, and each of them can provide different information about the planets orbiting the star. Some of them are:

Astrometry: this method consists in measuring the position of the star during a period of time and seeing how its position changes. In the simple case of a star orbited by a single planet, both the star and the planet orbit their mutual center of mass, as shown in fig. 1. This method works best when the plane of the planet's orbit is perpendicular to our line of sight, and then the star's wobble is maximal. This is not a commonly used method to discover exoplanets, because it is still difficult to obtain the needed measurements.

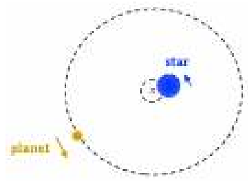

Fig. 1: a planet and its parent star, orbiting around their common center of mass.

The amplitude of the wobble (in mili arcsec) is proportional to the mass of the planet, the radius of the orbit, and inversely proportional to the distance between the star and Earth. For example: a star at 10pc from Earth with a Jupiter-mass planet, at an orbit of radius 5AU, will have a wobble of 0.5 mili arcsec. With respect to Doppler technique (explained below), this method has an advantage: the wobble is proportional to the radius, so when using this

[1] Habitable Zone is the zone around a star in which the temperatures are adequate to sustain liquid water, and hence, sustain life as we know it.

[2] The planets may be seen in infrared wave lengths.

method, planets with higher orbital radius can be detected. With this method, the mass, orbital radius, and inclination of the planet can be calculated.

Radial Velocity (RV): this is a spectroscopic method, and it uses the Doppler Effect. When a star moves with respect to Earth (because of the tug exerted by a planet), by measuring the displacement of its spectral lines[3] as a function of time, its radial velocity (velocity with which the star moves towards or away from Earth) can be calculated. For example, the Sun wobbles at a speed of ~13 m s^{-1} (mostly because of Jupiter's and Saturn's perturbations). If $\Delta\lambda$ is the Doppler shift in the measured wavelength, and λ is the wavelength when there is no shift, then the radial velocity is: (1) $v_r(t) = \frac{\Delta\lambda(t)}{\lambda}c$, where c is the speed of light. The semi-amplitude K and the period P are related to the Mass of the planet, M_p, by the formula:

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

where e is the eccentricity of the orbit, M_s the stellar mass (which is already known) and i is the inclination of the orbit relative to the line of sight (i close to 90º when the system is seen edge-on).

From the velocities measured, a radial-velocity curve is drawn, and then it's fitted[4] to formula (2) (example shown in fig. 2). The fit gives a minimum mass of the planet ($M_p \sin i$, because in most cases i is not known), the orbital period and the eccentricity of the orbit. Because the semi-amplitude is proportional to $P^{-1/3}$, this method is best to find short period (i.e. small orbit) planets.

In some cases, after making the fit, there are some velocity residuals. When the fit is subtracted from the data, these residuals show another radial-velocity curve. This new curve belongs to another planet orbiting the same star, with a much higher period (i.e. larger radius) which means, a smaller effect on the star.

[3] We already know how the spectrum of different types of stars looks.

[4] The curve is fitted to a periodic function, with semi amplitude K and period P. Then the rest of the parameters in (2) are calculated to obtain the best fit.

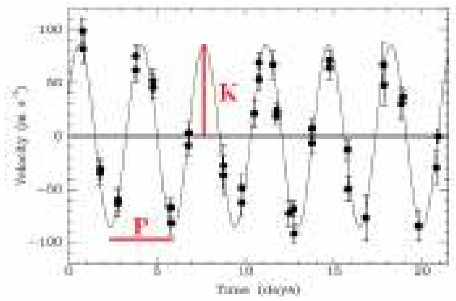

Fig. 2: radial velocity curve and its fit, for star HD209458.

Transits (or photometry): in certain occasions, the plane of the planet's orbit is aligned with our line of view ($i \cong 90°$). In those cases, once in every orbit, the planet will pass in front of (or transit) the disk of the star, lowering its brightness by a small percentage. When a transit is spotted, by measuring the decrease in brightness and the durations of the transit, ingress and egress (in fig. 3: intervals 3, 1 and 2, respectively), the size of the planet and the star can be derived.

The probability of discovering transiting planets is not high: the planet has to have an inclination close to 90º, and it has to be in an orbit not far from its parent star[5]. For Jupiter-like planets, the radius of the planet is ~10% of the star's radius, producing a decrease of 0.3-3.0% in the flux during the transit, which lasts 1.5-3.5 hours.

From this method, the mass of the planet can't be measured, therefore, after a transiting planet is discovered, RV measurements are also taken. Moreover, since the inclination i is near 90º, the exact mass of the planet can be known. From combining the two methods, the density of the planet can also be calculated, which gives information about the planet's composition (gas planet or rocky planet, for example).

Furthermore, by taking infrared spectra of the planet and its parent star before the transit, during the transit and during the occultation[6], and comparing between them, the temperature of the planet can be calculated, and information about its atmosphere composition can be obtained[7].

[5] The probability is proportional to the sum of the star's and planet's radiuses, and inversely proportional to the orbital radius.

[6] Occultation occurs when the planet passes behind the star.

[7] Even the presence of clouds can be detected.

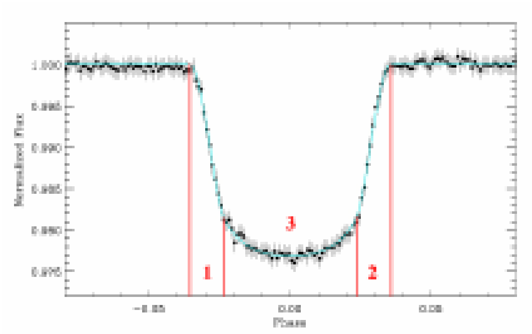

Fig. 3: Normalized brightness of a star as function of Phase (since middle of transit).

When using this method, a large field of stars can be monitored at the same time, and even small telescopes can be used.
However, this method suffers from a high rate of false detections (i.e. the companion is not a planet, but a smaller star, like brown dwarfs). Every time a planet candidate is discovered using this method, it has to be verified using other methods (usually, RV).
Gravitational microlensing: as predicted by Einstein, massive bodies can bend light. When a star passes in front of a background star, the first amplifies the brightness of the background one. If the first one has a planet, it will add to the amplification effect, as shown in fig. 4. With this method, a large amount of stars can be monitored at the same time. Usually, the source (background) stars monitored, are located near the center bulge of the galaxy, where the star density is higher. From this method, besides the planet and star masses, not much information can be acquired: the lens star is usually too faint to be seen and followed after the microlensing event, and each event happens only once. But using this technique allows us to find exoplanets at farther distances from Earth than with other methods.

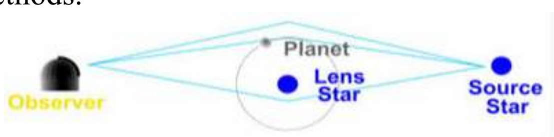

Fig. 4: the observer sees the Source Star amplified by the Lens Star and its Planet.

Findings, Results and Repercussions
The first exoplanet found, orbits around the Sun-like star 51 Pegasi. It has a minimum mass of 0.468 M_J (Jupiter masses), a period of 4.23 days, orbital radius of 0.052 AU and zero eccentricity. For comparison: in our solar system, Jupiter's and Mercury's orbital radiuses are 5.2 AU and 0.38 AU respectively, meaning that the planet discovered has almost the mass of Jupiter, but orbits its parent star closer than Mercury does the Sun! None of our planet formation theories could explain that. This first planet is not one of a kind: most of the exoplanets found are as massive as Jupiter, or even more, and most of them have small orbital radiuses. This short-period, Jupiter-like planets are called "Hot Jupiters".
However, that most of the exoplanets found are gas giants doesn't mean that the Solar system, having four giants and four terrestrial planets, is unique: as I explained, our methods have their limitations. For example, when using the RV method, to find Jupiter-mass planets, the resolution of the spectrograph has to be at least 10m sec^{-1}. The Sun's semi-amplitude because of Earth's perturbation is ~0.1m sec^{-1}, meaning that to find Earth-mass planets the resolution has to be much higher. With respect to transits, if the planet is too small, the decrease in brightness will not be enough to be noticed. But more important is the fact that sometimes stars have variable brightness that produces changes similar to those an Earth-like planet would produce, like pulsations, or even sun spots.
In addition, to be certain that a candidate is really a planet (and not a random event), we need to see at least two full orbits. Jupiter's period is almost 12 years, and the first exoplanet was discovered only 12 years ago, which means that planets with longer periods (and larger orbital radiuses) are more difficult to discover.
One of the biggest problems in detecting exoplanets is that other astronomical objects can produce similar effects on their parent star, for example, a binary star system may produce a transit similar to that a planet will produce. But the most common objects mistakenly classified as exoplanets are Brown Dwarfs. Those are a kind of failed stars, with masses between 13 and 80 M_J[8].
From all the findings, new theories have been formulated, and some old ones, were updated. The standard model of planet formation tells

[8] Stars above 80M_J can burn Hydrogen, below that, only Deuterium can be burned; however, it's still not clear if 13M_J is the real limit between Brown Dwarf and Planet.

that gas giants (around Sun-like stars) are created at a distance of 4 AU or more from the star, and rocky planets are created closer than that, because of the differences in temperature, components, and in the density of matter in the planetary disk. In addition, all orbits are circular and in the same plane. Finally, more than one planet will be formed. Some of our findings don't agree with this. For example, there are many planets with high eccentricity (elliptical orbits), and giants orbiting closer than 4 AU. Also, although some systems with more than one planet have been found, most of the planetary systems discovered have only one planet.

The reason for the last is, again, our limitations: those systems may have more planets that we could not detect just yet. Since the creation of a giant planet takes more time than the creation of terrestrial planets, it's now believed that if a system has giants, it also must have terrestrials. Gas giants form around solid cores (made of rocks, metals or ice). So, if in a planetary disk, for some reason the gas is depleted very fast, the system will be left over with only terrestrial, small planets.

Some facts about orbit eccentricities in exoplanets[9]: most exoplanets within 0.1 AU have circular orbits, and beyond 0.1 AU, there is a uniform distribution of eccentricities between 0 and 0.8. Some explanations for high eccentricity orbits have been formulated. The most accepted are: Planet-Planet interactions, and gravitational perturbations from a companion star (in binary systems), or from a passing star. The reason for zero eccentricities in small orbits is believed to be tidal forces between the planet and the star that lower the eccentricity until the planet remains in a circular orbit.

With respect to "Hot Jupiters": the most accepted theory is Migration, where a planet is formed far from its parent star, but falls into a smaller orbit. There are two types of migrations: Type I, which deals with migration of terrestrial planets, and Type II, which explains migration of planets of more than 10 Earth masses. I will explain only Type II since giants belong to this category. During planet formation, massive planets clear gaps in the planetary disk. After the gap is created, the planet "gives away" and "receives" part of its orbital momentum to the matter around it, in such a way that in total, the planet losses momentum. Since momentum is proportional to the radius of the orbit, a decrease in momentum produces a decrease in orbital radius, and the planet falls. Sometimes, if there is enough matter on the disk, this fall may end with the planet crashing into the star. In other cases, the migration may stop because all the matter is cleared. But there is also an interesting fact: between all the Hot Jupiters, most of them have periods of ~3 days, which means that there may be a mechanism that stops the fall at that point. One possibility is interactions between the planet and the star, which may circularize the orbit and stop the migration.

[9] For comparison: Jupiter and the other giant planets in the Solar system have eccentricities of less than 0.05.

Conclusion and Future Prospects

There are exoplanets that orbit normal stars, giant stars, dwarf stars, and even double stars. There are water worlds, gas worlds and even terrestrial worlds. There are young planets (probably even less than 1 million years old), and ancient ones (probably 13 billion years old). One exoplanet even had his whole surface temperature mapped.

All those discoveries have changed the way we think about many topics. We know that we are not unique. In addition, many of our theories have been reformulated or improved, and new ones proposed.

In the last years, technology has advanced at light speed, and thanks to that, smaller, farther and more special worlds are being found every week. Because of that, findings of some not-so-special exoplanets are not even published in popular science journals. Right now, there is a European space telescope, COROT, whose main goal is search for transiting planets. There are even plans to launch telescopes dedicated just to find Earth-like planets, like the Kepler Mission. Some of them will try to directly see them, using infrared light and interferometers to "erase" the star.

In conclusion, the way I see it, in the next few years, the number of exoplanets will grow in a way we couldn't predict 12 years ago, when the first one was found.

Bibliography
- A Decade of Radial-Velocity Discoveries in the Exoplanet Domain (Udry et al, 2007).
- When Extra Solar Planets Transit Their Parent Stars (Charbonneau et al, 2006).
- Observations of Extrasolar Planetary Systems (Zucker, 2007).
- Detection of Extrasolar Giant Planets (Marcy et al, 1998).
- Astronomical Searches for Earth-Like Planets and Signs of Life (Woolf et al, 1998).
- http://www.sapce.com
- http://www.exoplanets.org
- http://www.wikipedia.org