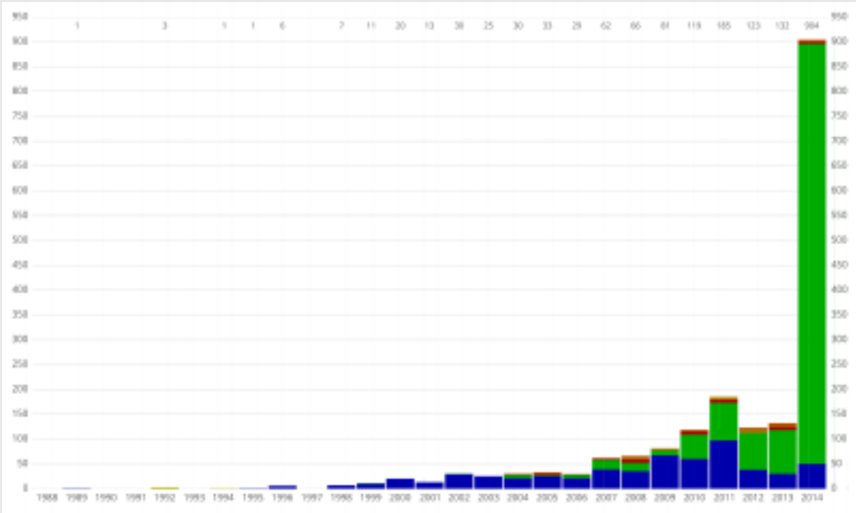
Methods of detecting exoplanets



Number of extrasolar planet discoveries per year through September 2014, with colors indicating method of detection:

Any planet has an extremely faint light source compared to its parent star. In addition to the intrinsic difficulty of detecting such a faint light source, the light from the parent star causes a glare that washes it out. For those reasons, very few of the extrasolar planets reported as of March 2014 have been observed directly, with even fewer being resolved from their host star.

Instead, astronomers have generally had to resort to indirect methods to detect extrasolar planets. At the present time, several different indirect methods have yielded success.

Established detection methods

The following methods have proved successful for discovering a new planet or detecting already discovered planet at least once:

Radial velocity

A star with a planet will move in its own small orbit in response to the planet's gravity. This leads to variations in the speed with which the star moves toward or away from Earth, i.e. the variations are in the radial velocity of the star with respect to Earth. The radial velocity can be deduced from the displacement in the parent star's spectral lines due to the Doppler effect. The radial-velocity method measures these variations in order to confirm the presence of the planet.

The velocity of the star around the system's center of mass is much smaller than that of the planet, because the radius of its orbit around the center of mass is so small. However, velocity variations down to 1 m/s or even somewhat less can be detected with modern spectrometers, such as the HARPS (High Accuracy Radial Velocity Planet Searcher) spectrometer at the ESO 3.6 meter telescope in La Silla Observatory, Chile, or the HIRES spectrometer at the Keck telescopes. An especially simple and inexpensive method for measuring radial velocity is "externally dispersed interferometry". [1]

Until the year 2014, the radial-velocity method was by far the most productive technique used by planet hunters. It is also known as Doppler spectroscopy. The method is distance independent, but requires high signal-to-noise ratios to achieve high precision, and so is generally only used for relatively nearby stars out to about 160 light-years from Earth to find lower-mass planets. It is also not possible to simultaneously observe many target stars at a time with a single telescope. Jovian mass planets can be detectable around stars up to a few thousand light years away. It easily finds massive planets that are close to stars. Modern spectrographs can also easily detect Jupiter-mass planets orbiting 10 astronomical units away from the parent star but detection of those planets requires many years of observation.

It is easier to detect planets around low-mass stars for two reasons: First, these stars are more affected by gravitational tug from planets. The second reason is that low-mass main-sequence stars generally rotate relatively slowly. Fast rotation makes spectral-line data less clear because half of the star quickly rotates away from observer's viewpoint whereas the other half closes in. Detecting planets around more massive stars is easier if the star has left the main sequence because leaving the main sequence slows down the star's rotation.

Sometimes Doppler spectrography produces false signals which is more common in multi-planet and multi-star systems. Magnetic field and certain types of stellar activity can also give false signals. When the host star has multiple planets, false signals can also arise from having insufficient data where multiple solutions can fit with gathered data as stars are not generally observed continuously.[2] Some of the false signals can be eliminated by analyzing the stability of the planetary system, conducting photometry analysis on the host star and knowing its rotation period and stellar activity cycle periods.

Planets with orbits highly inclined to the line of sight from Earth produce smaller wobbles, and are thus more difficult to detect. One of the advantages of radial velocity method is that eccentricity of the planet's orbit can be measured directly. One of the main disadvantages of the radial-velocity method is that it can only estimate a planet's minimum mass (

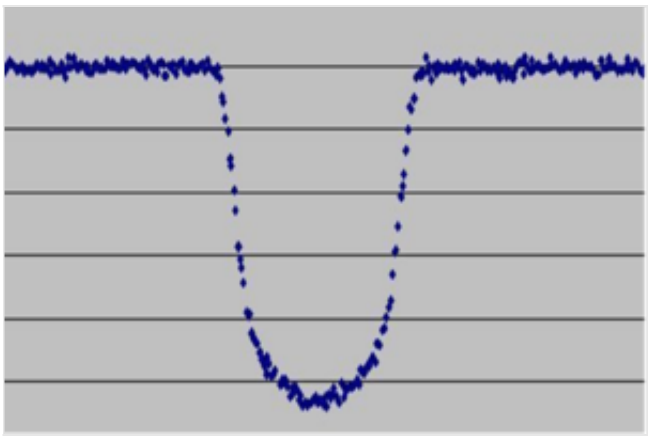
$$M_{\text{true}} * \sin i$$

). The posterior distribution of the inclination angle *i* depends on the true mass distribution of the planets.[3] However, when multiple planets are present in the system that orbit relatively close to each other and have sufficient mass, orbital stability analysis allows to constrain the maximum mass of the planets in question. The radial-velocity method can be used to confirm findings made by using the transit method. When both methods are used in combination, then the planet's true mass can be estimated.

Although radial-velocity of the star only gives a planet's minimum mass, if the planet's spectral lines can be distinguished from the star's spectral lines then the radial-velocity of the planet itself can be found and this gives the inclination of the planet's orbit. This allows measure planet's actual mass. This also rules out false positives and allows to gain information about the composition of the planet. The main issue is that such detection is only possible if the planet orbits around relatively bright star and if the planet reflects or emits a lot of light.[4]

Transit photometry

See also: List of transiting exoplanets



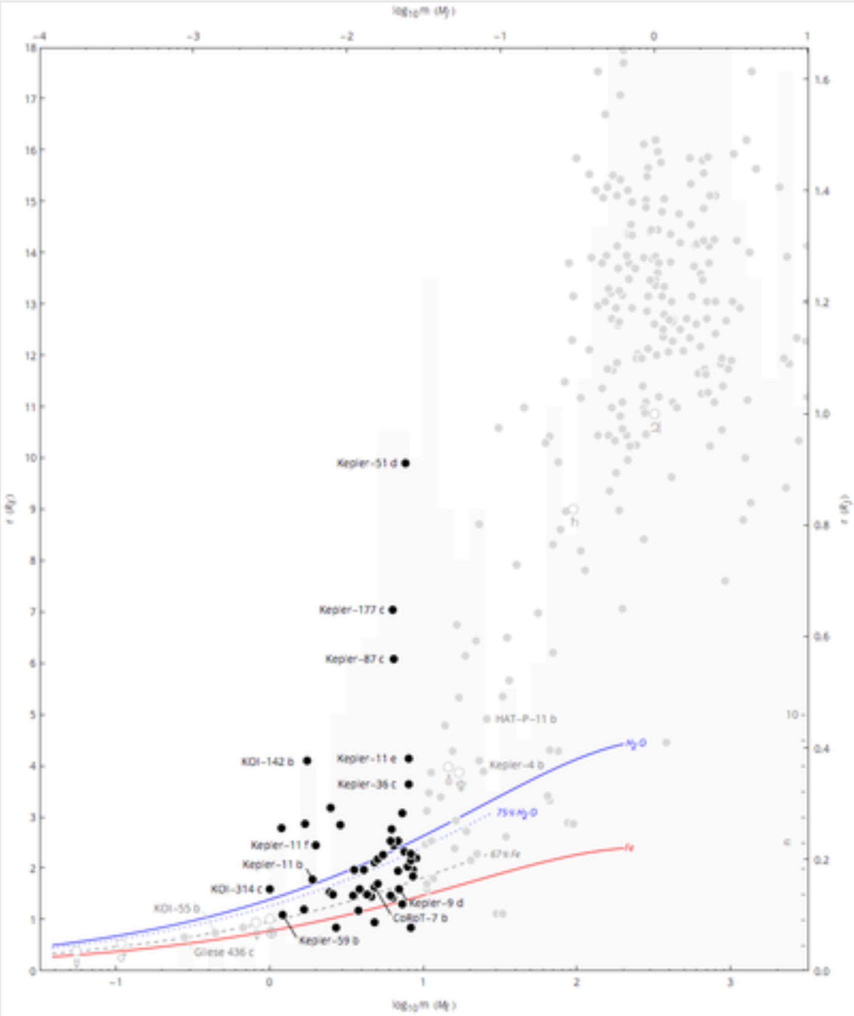
Kepler 6b photometry.[5]

While the above methods provide information about a planet's mass, this photometric method can determine the radius of a planet. If a planet crosses (transits) in front of its parent star's disk, then the observed visual brightness of the star drops a small amount. The amount the star dims depends on the relative sizes of the star and the planet. For example, in the case of HD 209458, the star dims 1.7%.

This method has two major disadvantages. First of all, planetary transits are only observable for planets whose orbits happen to be perfectly aligned from the astronomers' vantage point. The probability of a planetary orbital plane being directly on the line-of-sight to a star is the ratio of the diameter of the star to the diameter of the orbit (in small stars, the radius of the planet is also an important factor). About 10% of planets with small orbits have such alignment, and the fraction decreases for planets with larger orbits. For a planet orbiting a Sun-sized star at 1 AU, the probability of a random alignment producing a transit is 0.47%. Therefore the method cannot guarantee that any particular star is not a host to planets. However, by scanning large areas of the sky containing thousands or even hundreds of thousands of stars at once, transit surveys can find extrasolar planets at a rate that exceeds that of the radial-velocity method.[6] Several surveys have taken that approach, such as the ground-based MEarth Project and HATNet and the space-based COROT and Kepler missions. Transit method has also an advantage of detecting planets around stars that are located a few thousand light years away. The most distant planets detected from Sagittarius Window Eclipsing Extrasolar Planet Search are located near the galactic center. However, reliable follow-up observations with these stars are nearly impossible with current technology.

Secondly, the method suffers from a high rate of false detections. A 2012 study found that the rate of false positives for transits observed by the Kepler mission could be as high as 40% in single planet systems.[7] For this reason, a star with a single transit detection requires additional confirmation, typically from the radial-velocity method or orbital brightness modulation method. Radial velocity method is especially necessary for Jupiter-sized or larger planets as objects of that size encompass not only planets, but also brown dwarfs and even small stars. As false positive rate is very low in stars with two or more planet candidates, they often can be validated without extensive follow-up observations. Some can also be confirmed through transit timing variation method.[8][9][10]

Red giant branch stars have another issue for detecting planets around them: while planets around these stars are much more likely to transit due to the larger size, these transit signals are hard to separate from the main star's brightness light curve as red giants have frequent pulsations in brightness with a period of few hours to days. This is especially notable with subgiants. In addition, these stars are much more luminous and transiting planets block much smaller percentage of light coming from these stars. In the contrary, planets can completely occult a neutron star or a white dwarf which would be easily detectable from Earth. However, due to their small sizes, chance of a planet aligning such a stellar remnant is extremely small.



Properties (mass and radius) of planets discovered using the transit method, compared with the distribution, n (light gray bar chart), of minimum masses of transiting and non-transiting exoplanets. Super-Earths are black

The main advantage of the transit method is that the size of the planet can be determined from the lightcurve. When combined with the radial-velocity method (which determines the planet's mass) one can determine the density of the planet, and hence learn something about the planet's physical structure. The planets that have been studied by both methods are by far the best-characterized of all known exoplanets.[11]

The transit method also makes it possible to study the atmosphere of the transiting planet. When the planet transits the star, light from the star passes through the upper atmosphere of the planet. By studying the high-resolution stellar spectrum carefully, one can detect elements present in the planet's atmosphere. A planetary atmosphere (and planet for that matter) could also be detected by measuring the polarisation of the starlight as it passed through or is reflected off the planet's atmosphere.

Additionally, the secondary eclipse (when the planet is blocked by its star) allows direct measurement of the planet's radiation and helps to constrain the planet's eccentricity without the presence of other planets. If the star's photometric intensity during the secondary eclipse is subtracted from its intensity before or after, only the signal caused by the planet remains. It is then possible to measure the planet's temperature and even to detect possible signs of cloud formations on it. In March 2005, two groups of scientists carried out measurements using this technique with the Spitzer Space Telescope. The two teams, from the Harvard-Smithsonian Center for Astrophysics, led by David Charbonneau, and the Goddard Space Flight Center, led by L. D. Deming, studied the planets TrES-1 and HD 209458b respectively. The measurements revealed the planets' temperatures: 1,060 K (790°C) for TrES-1 and about 1,130 K (860 °C) for HD 209458b. [12][13] In addition the hot Neptune Gliese 436 b enters secondary eclipse. However some transiting planets orbit such that they do not enter secondary eclipse relative to Earth; HD 17156 b is over 90% likely to be one of the latter.

A French Space Agency mission, COROT, began in 2006 to search for planetary transits from orbit, where the absence of atmospheric scintillation allows improved accuracy. This mission was designed to be able to detect planets "a few times to several times larger than Earth" and performed "better than expected", with two exoplanet discoveries[14] (both "hot jupiter" type) as of early 2008. In June 2013, CoRoT's exoplanet count was 32 with several still to be confirmed. The satellite unexpectedly stopped transmitting data in November, 2012 (after its mission had twice been extended) and is currently being decommissioned with final shut-off scheduled for spring 2014.[15]

In March 2009, NASA mission Kepler was launched to scan a large number of stars in the constellation Cygnus with a measurement precision expected to detect and characterize Earth-sized planets. The NASA Kepler Mission uses the transit method to scan a hundred thousand stars in the constellation Cygnus for planets. It was hoped that by the end of its mission of 3.5 years, the satellite would have collected enough data to reveal planets even smaller than Earth. By scanning a hundred thousand stars simultaneously, it was not only able to detect Earth-sized planets, it was able to collect statistics on the numbers of such planets around Sun-like stars.[16]

On February 2, 2011, the Kepler team released a list of 1,235 extrasolar planet candidates, including 54 that may be in the habitable zone. On December 5, 2011, the Kepler team announced that they had discovered 2,326 planetary candidates, of which 207 are similar in size to Earth, 680 are super-Earth-size, 1,181 are Neptune-size, 203 are Jupiter-size and 55 are larger than Jupiter. Compared to the February 2011 figures, the number of Earth-size and super-Earth-size planets increased by 200% and 140% respectively. Moreover, 48 planet candidates were found in the habitable zones of surveyed stars, marking a decrease from the February figure; this was due to the more stringent criteria in use in the December data. By the June of 2013, the number of planet candidates was increased to 3,278 and some confirmed planets were smaller than Earth, some even Mars-sized (such as Kepler-62c) and one even smaller than Mercury (Kepler-37b).[17]

Reflection/emission modulations (direct non-resolved detection)

Short-period planets in close orbits around their stars will undergo reflected light variations changes because, like the Moon, they will go through phases from full to new and back again. In addition, as these planets receive a lot of starlight, it heats them, making thermal emissions potentially detectable. Since telescopes cannot resolve the planet from the star, they see only the combined light, and the brightness of the host star seems to change over each orbit in a periodic manner. Although the effect is small — the photometric precision required is about the same as to detect an Earth-sized planet in transit across a solar-type star – such Jupiter-sized planets with an orbital period of a few days are detectable by space telescopes such as the Kepler Space Observatory. Like with transit method, it is easier to detect large planets orbiting close to their parent star than other planets as these planets catch more light from their parent star. When planet has a high albedo and is situated around relatively luminous star, its light variations are easier to detect in visible light while darker planets or planets around low-temperature stars are more easily detectable with infrared light with this method. In the long run, this method may find the most planets that will be discovered by that mission because the reflected light variation with orbital phase is largely independent of orbital inclination of the planet's orbit and does not require the planet to pass in front of the disk of the star. It still cannot detect planets with circular face-on orbits from Earth's viewpoint as the amount of reflected light does not change during its orbit.

The phase function of the giant planet is also a function of its thermal properties and atmosphere, if any. Therefore the phase curve may constrain other planet properties, such as the particle size distribution of the atmospheric particles. When planet is found transiting and its size is known, phase variations curve helps calculate or constrain planet's albedo. It is more difficult with very hot planets as the glow of the planet can interfere when trying to calculate the albedo of the planet. In theory, albedo can also be found in non-transiting planets when observing the light variations with multiple wavelengths. This allows to find the size of the planet even if the planet is not transiting the star.[18]

The first-ever direct detection of the spectrum of visible light reflected from an exoplanet has been made by an international team of astronomers. The astronomers studied light from 51 Pegasi b – the first exoplanet discovered orbiting a main-sequence star (a Sunlike star), using the High Accuracy Radial velocity Planet Searcher (HARPS) instrument at the European Southern Observatory's La Silla Observatory in Chile.[19][20]

Both Corot[21] and Kepler[22] have measured the reflected light from planets. However, these planets were already known since they transit their host star. The first planets discovered by this method are Kepler-70b and Kepler-70c, found by Kepler.[23]

Light variations due to relativistic beaming

A separate novel method to detect exoplanets from light variations uses relativistic beaming of the observed flux from the star due to its motion. It is also known as Doppler beaming or Doppler boosting. The method was first proposed by Abraham

Loeb and Scott Gaudi in 2003 .[24] As the planet tugs the star with its gravitation, the density of photons and therefore the apparent brightness of the star changes from observer's viewpoint. Like using radial velocity method, it can be used to determine the orbital eccentricity and the minimum mass of the planet and it is easier to detect massive planets close to their stars as these factors increase star's motion. Unlike radial velocity method, it does not require accurate spectrum of a star and therefore can be used more easily to find planets around fast-rotating stars and more distant stars.

One of the biggest disadvantages of this method is that the effect on light variations is very small. A Jovian-mass planet orbiting 0.025 AU away from a Sun-like star is barely detectable even when the orbit is edge-on. It is unlikely that new planets can be found with this method as the amount of emitted and reflected starlight from the planet is usually much larger than light variations due to relativistic beaming. This method is still useful as it allows to measure the planet's mass without the need of follow-up data collection from radial velocity observations.

The first discovery of a planet based on this method (Kepler-76b) was announced in 2013.[25][26]

Light variations due to ellipsoidal variations

Massive planets can cause slight tidal distortions to their host stars. When a star has a slight ellipsoidal shape, its apparent brightness varies, depending if the oblate part of the star is facing the observer's viewpoint. Like with the relativistic beaming method, it helps to determine the minimum mass of the planet and its sensitivity depends on the planet's orbital inclination. The extent of the effect on a star's apparent brightness can be much larger than with the relativistic beaming method but the brightness changing cycle is twice as fast. In addition, the [*clarification needed*]distorts the shape of the star more if it has a low semi-major axis to stellar radius ratio and the density of the star is low. This makes this method suitable for finding planets around stars that have left the main sequence.[27]

Timing variations

Orbiting planets can cause variations of durations of periodic phenomena on stars or other planets orbiting them.

Pulsar timing

See also: List of exoplanets detected by timing

A pulsar is a neutron star: the small, ultradense remnant of a star that has exploded as a supernova. Pulsars emit radio waves extremely regularly as they rotate. Because the intrinsic rotation of a pulsar is so regular, slight anomalies in the timing of its observed radio pulses can be used to track the pulsar's motion. Like an ordinary star, a pulsar will move in its own small orbit if it has a planet. Calculations based on pulse-timing observations can then reveal the parameters of that orbit.[28]

This method was not originally designed for the detection of planets, but is so sensitive that it is capable of detecting planets far smaller than any other method can, down to less than a tenth the mass of Earth. It is also capable of detecting mutual gravitational perturbations between the various members of a planetary system, thereby revealing further information about those planets and their orbital parameters. In addition, it can easily detect planets which are relatively far away from pulsar.

The are two main drawbacks of the pulsar-timing method: Pulsars are relatively rare (they are too small to be discovered in a mass number, therefore are seen as rare celestial bodies) and special circumstances are required for a pulsar planet to form so it is unlikely that a large number of planets will be found this way.[29] Also, life *as we know it* could not survive on planets orbiting pulsars since high-energy radiation there is extremely intense.

In 1992 Aleksander Wolszczan and Dale Frail used this method to discover planets around the pulsar PSR 1257+12.[30] Their discovery was quickly confirmed, making it the first confirmation of planets outside our Solar System.

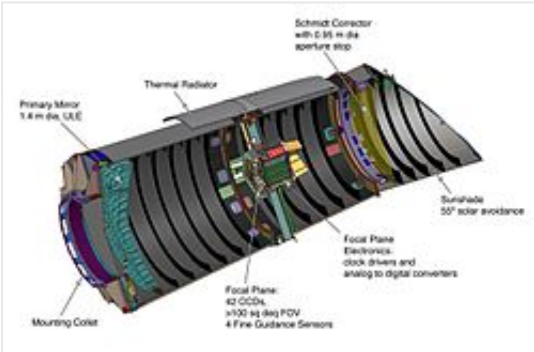
Pulsation frequency (variable star timing)

Like pulsars, some other types of pulsating variable stars are regular enough that radial velocity could be determined purely photometrically from the Doppler shift of the pulsation frequency, without needing spectroscopy.[31][32] This method is not as sensitive as pulsar timing variation method due to periodic activity being longer and less regular. The ease of detecting the planet around variable star depends on the pulsation period of the star, the regularity of pulsations, the mass of a planet and its distance from the host star.

The first success came in 2007 when a planet was discovered around a pulsating subdwarf star V391 Pegasi b.[33]

Transit timing variation method (TTV)

Main article: Transit timing variation



The Kepler Mission, A NASA mission which is able to detect extrasolar planets

"Timing variation" asks whether the transit occurs with strict periodicity or if there's a variation. When multiple transiting planets are detected, they can often be confirmed with transit-timing variation method. This is useful in planetary systems far away from the Sun where radial velocity methods cannot detect them due to low signal-to-noise ratio. If a planet has been detected by the transit method, then variations in the timing of the transit provide an extremely sensitive method which is capable of detecting additional non-transiting planets in the system with masses comparable to Earth's. It is easier to detect transit-timing variations if planets have relatively close orbits and when at least one of the planets is more massive, causing the orbital period of a less massive planet to be more perturbed.[34][35][36]

The main drawback of transit-timing method is that usually not much can be learned about the planet itself. Transit-timing variation can help to determine the maximum mass of the planet. In most cases, it can confirm if an object has a planetary mass but it does not put narrow constraints to it. There are exceptions though as planets in Kepler-36 and Kepler-88 system orbit close enough to accurately determine their mass.

The first significant detection of a non-transiting planet using TTV was carried out with NASA's Kepler satellite. The transiting planet Kepler-19b shows TTV with an amplitude of 5 minutes and a period of about 300 days, indicating the presence of a second planet, Kepler-19c, which has a period which is a near rational multiple of the period of the transiting planet [37][38]

In circumbinary planets, variations of transit timing are mainly caused by the orbital motion of the stars instead of gravitational perturbations of other planets. These variations make it harder to detect these planets through automated methods. However, it makes these planets to be easily confirmed once detected.

Transit duration variation method (TDV)

"Duration variation" refers to changes in how long the transit takes. Duration variations may be caused by an exomoon, or apsidal precession for eccentric planets due to another planet in the same system or general relativity.[39][40]

When a circumbinary planet is found through transit method, it can be easily confirmed with transit duration variation method.[41] In close binary systems, the stars significantly alter the motion of the companion, meaning that any transiting planet has significant differences in transit duration. The first such confirmation came from Kepler-16b.[42]

Eclipsing binary minima timing

When a binary star system is aligned such that – from the Earth's point of view – the stars pass in front of each other in their orbits, the system is called an "eclipsing binary" star system. The time of minimum light, when the star with the brighter surface area is at least partially obscured by the disc of the other star, is called the primary eclipse, and approximately half an orbit later, the secondary eclipse occurs when the brighter surface area star obscures some portion of the other star. These times of minimum light, or central eclipse, constitute a time stamp on the system, much like the pulses from a pulsar (except that rather than a flash, they are a dip in the brightness). If there is a planet in circum-binary orbit around the binary stars, the stars will be offset around a binary-planet center of mass. As the stars in the binary are displaced by the planet back and forth, the times of the eclipse minima will vary; they will be too late, on time, too early, on time, too late, etc.. The periodicity of this offset may be the most reliable way to detect extrasolar planets around close binary systems.[43][44][45] With this method, planets are more easily detectable if they are more massive, orbit relatively closely around the system and if stars have low masses.

Eclipsing timing method allows the detection of planets further away from host star than transit method. However, signals around cataclysmic variable stars hinting for planets tend to match with unstable orbits.[46] In 2011, Kepler-16b became the first planet with which was definitely characterized through eclipsing binary timing variations.[47]

Gravitational microlensing

Gravitational microlensing occurs when the gravitational field of a star acts like a lens, magnifying the light of a distant background star. This effect occurs only when the two stars are almost exactly aligned. Lensing events are brief, lasting for weeks or days, as the two stars and Earth are all moving relative to each other. More than a thousand such events have been observed over the past ten years.

If the foreground lensing star has a planet, then that planet's own gravitational field can make a detectable contribution to the lensing effect. Since that requires a highly improbable alignment, a very large number of distant stars must be continuously monitored in order to detect planetary microlensing contributions at a reasonable rate. This method is most fruitful for planets between Earth and the center of the galaxy, as the galactic center provides a large number of background stars.

In 1991, astronomers Shude Mao and Bohdan Paczyński proposed using gravitational microlensing to look for binary companions to stars, and their proposal was sharpened by Andy Gould and Abraham Loeb in 1992 as a method to detect exoplanets. Successes with the method date back to 2002, when a group of Polish astronomers (Andrzej Udalski, Marcin Kubiak and Michał Szymański from Warsaw, and Bohdan Paczyński) during project OGLE (the Optical Gravitational Lensing Experiment) developed a workable technique. During one month they found several possible planets, though limitations in the observations prevented clear confirmation. Since then, several confirmed extrasolar planets have been detected using microlensing. This was the first method capable of detecting planets of Earthlike mass around ordinary main-sequence stars.[48]

Unlike most other methods which have detection bias towards planets with small (or for resolved imaging, large) orbits, microlensing method is most sensitive to detecting planets around 1-10 astronomical units away from Sun-like stars.

A notable disadvantage of the method is that the lensing cannot be repeated because the chance alignment never occurs again. Also, the detected planets will tend to be several kiloparsecs away, so follow-up observations with other methods are usually impossible. In addition, the only physical characteristic that can be determined by microlensing are loose constraints of a mass of the planet. Orbital properties also tend to be unclear as the only orbital characteristic that can be directly determined is its current semi-major axis from the parent star which can be misleading if the planet follows an eccentric orbit. When the planet is far away from its star, it spends only a tiny portion of its orbit in a state where it is detectable with this method so orbital period of the planet cannot be easily determined. It is also easier to detect planets around low-mass stars as it increases planet-to-star mass ratio and thus gravitational microlensing effect is greater.

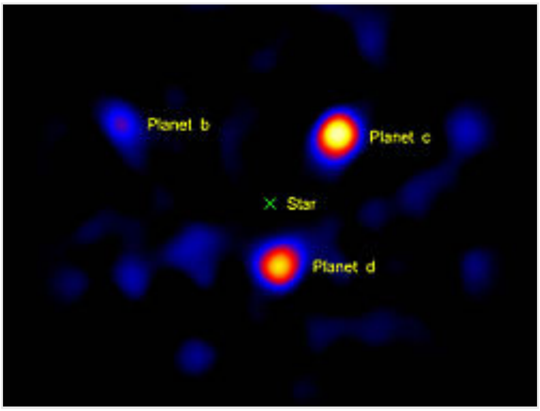
The main advantages of gravitational microlensing method are that it can detect planets with face-on orbits from Earth's viewpoint and it can detect planets around very distant stars. When enough background stars can be observed with enough accuracy then the method should eventually reveal how common earth-like planets are in the galaxy.

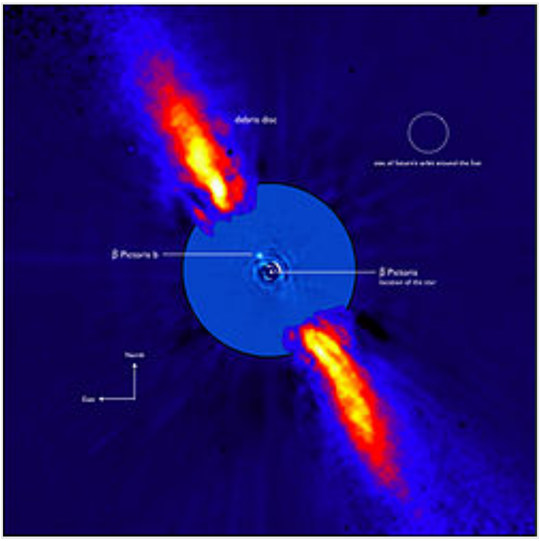
Observations are usually performed using networks of robotic telescopes. In addition to the European Research Council-funded OGLE, the Microlensing Observations in Astrophysics (MOA) group is working to perfect this approach.

The PLANET (Probing Lensing Anomalies NETwork)/RoboNet project is even more ambitious. It allows nearly continuous round-the-clock coverage by a world-spanning telescope network, providing the opportunity to pick up microlensing contributions from planets with masses as low as Earth. This strategy was successful in detecting the first low-mass planet on a wide orbit, designated OGLE-2005-BLG-390Lb.[48]

Direct imaging

See also: List of directly imaged exoplanets





ESO image of a planet near Beta Pictoris.

As mentioned previously, planets are extremely faint light sources compared to stars and what little light comes from them tends to be lost in the glare from their parent star. So in general, it is very difficult to detect and resolve them directly from their host star. Planets orbiting far enough from stars to be resolved reflect very little starlight so planets are detected through their thermal emission instead. It is easier to obtain images when the star system is relatively near to the Sun, the planet is especially large (considerably larger than Jupiter), widely separated from its parent star, and hot so that it emits intense infrared radiation; the images have then been made at infrared where the planet is brighter than it is at visible wavelengths. Coronagraphs are used to block light from the star while leaving the planet visible. During the accretion phase of planetary formation the star-planet contrast may be even better in H alpha than it is in infrared - an H alpha survey is currently underway.[49]

Direct imaging can give only loose constraints of the planet's mass which is derived from the age of the star and the temperature of the planet. Mass can vary considerably as planets can form several million years after the star has formed. The cooler the planet is, the less the planet's mass needs to be. In some cases it is possible to give reasonable constraints to the radius of a planet based on planet's temperature, its apparent brightness and its distance from Earth. The spectra emitted from planets do not have to be separated from the star which eases determining the chemical composition of planets.

Sometimes observations at multiple wavelengths are needed to rule out the planet being a brown dwarf. Direct imaging can be used to accurately measure the planet's orbit around the star. Unlike majority of other methods, direct imaging works better with planets with face-on orbits rather than edge-on orbits as face-on orbit is more easily observable during the entirety of the planet's orbit while planets with edge-on orbits are more easily observable during their largest apparent separation from the parent star.

The planets detected through direct imaging currently fall into two categories. First ones are found around stars more massive than the Sun which are young enough to have protoplanetary disks. The second ones are possible sub-brown dwarfs found around very dim stars or brown dwarfs and are at least 100 AU away from their parent stars.

Planetary-mass objects not gravitationally bound to a star are found through direct imaging as well.

Early discoveries

In 2004, a group of astronomers used the European Southern Observatory's Very Large Telescope array in Chile to produce an image of 2M1207b, a companion to the brown dwarf 2M1207.[50] In the following year the planetary status of the companion was confirmed.[51] The planet is believed to be several times more massive than Jupiter and to have an orbital radius greater than 40 AU.

In September 2008, an object was imaged at a separation of 330AU from the star 1RXS J160929.1−210524, but it was not until 2010 that it was confirmed to be a companion planet to the star and not just a chance alignment.[52]

The first multiplanet system, announced on 13 November 2008, was imaged in 2007 using telescopes at both Keck Observatory and Gemini Observatory. Three planets were directly observed orbiting HR 8799, whose masses are approximately 10, 10 and 7 times that of Jupiter.[53][54] On the same day, 13 November 2008, it was announced that the Hubble Space Telescope directly observed an exoplanet orbiting Fomalhaut with mass no more than 3 M_J.[55] Both systems are surrounded by disks not unlike the Kuiper belt.

In 2009 it was announced that analysis of images dating back to 2003 revealed a planet orbiting Beta Pictoris.

In 2012 it was announced that a "Super-Jupiter" planet with a mass about 12.8 M_J orbiting Kappa Andromedae was directly imaged using the Subaru Telescope in Hawaii.[56][57] It orbits its parent star at a distance of about 55 astronomical units, or nearly twice the distance of Neptune to the sun.

An additional system, GJ 758, was imaged in November 2009, by a team using the HiCIAO instrument of the Subaru Telescope but it was a brown dwarf.[58]

Other possible exoplanets to have been directly imaged: GQ Lupi b, AB Pictoris b, and SCR 1845 b.[59] As of March 2006 none have been confirmed as planets; instead, they might themselves be small brown dwarfs.[60][61]

Imaging instruments

Some projects to equip telescopes with planet-imaging-capable instruments include: the ground-based telescopes Gemini Planet Imager, VLT-SPHERE, Subaru-HiCIAO, Palomar Project 1640, and the space telescope WFIRST-AFTA.

In 2010 a team from NASAs Jet Propulsion Laboratory demonstrated that a vortex coronagraph could enable small scopes to directly image planets.[63] They did this by imaging the previously imaged HR 8799 planets using just a 1.5 m portion of the Hale Telescope.

Another promising approach is nulling interferometry.[64]

It has also been proposed that space-telescopes that focus light using zone plates instead of mirrors would provide higher-contrast imaging and be cheaper to launch into space due to being able to fold up the lightweight foil zone plate.[65]

Polarimetry

Main article: Polarimetry

Light given off by a star is un-polarized, i.e. the direction of oscillation of the light wave is random. However, when the light is reflected off the atmosphere of a planet, the light waves interact with the molecules in the atmosphere and they are polarized.

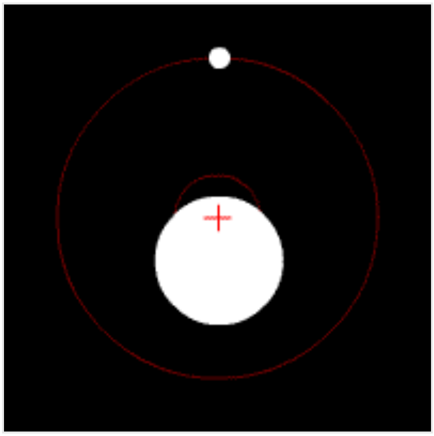
[66]

By analyzing the polarization in the combined light of the planet and star (about one part in a million), these measurements can in principle be made with very high sensitivity, as polarimetry is not limited by the stability of the Earth's atmosphere. Another main advantage is that polarimetry allows to determine the composition of the planet's atmosphere. The main disadvantage is that it will not be able to detect planets without atmosphere. Larger planets and planets with higher albedo are easier to detect through polarimetry as they reflect more light.

Astronomical devices used for polarimetry, called polarimeters, are capable of detecting the polarized light and rejecting the unpolarized beams (starlight). Groups such as ZIMPOL/CHEOPS[67] and PlanetPol[68] are currently using polarimeters to search for extra-solar planets. First success of detecting extrasolar planet using this method came in 2008 when HD 189733 b, a planet discovered 3 years before was detected using polarimetry.[69] However, no new planets have yet been discovered using this method.

Astrometry

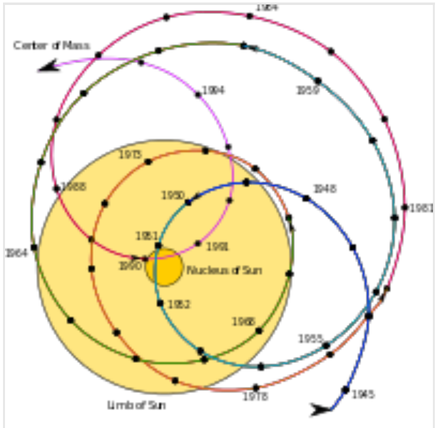
Main article: Astrometry



In this diagram a planet (smaller object) orbits a star, which itself moves in a small orbit. The system's center of mass is shown with a red plus sign. (In this case, it always lies within the star.)

This method consists of precisely measuring a star's position in the sky and observing how that position changes over time. Originally this was done visually with hand-written records. By the end of the 19th century this method used photographic plates, greatly improving the accuracy of the measurements as well as creating a data archive. If the star has a planet, then the gravitational influence of the planet will cause the star itself to move in a tiny circular or elliptical orbit. Effectively, star and planet each orbit around their mutual center of mass (barycenter), as explained by solutions to the two-body problem. Since the star is much more massive, its orbit will be much smaller.[70] Frequently, the mutual center of mass will lie within the radius of the larger body. Consequently, it is easier to find planets around low-mass stars and especially brown dwarfs.

Astrometry is the oldest search method for extrasolar planets and originally popular because of its success in characterizing astrometric binary star systems. It dates back at least to statements made by William Herschel in the late 18th century. He claimed that an *unseen companion* was affecting the position of the star he cataloged as *70 Ophiuchi*. The first known formal astrometric calculation for an extrasolar planet was made by W. S. Jacob in 1855 for this star.[71] Similar calculations were repeated by others for another half-century[72] until finally refuted in the early 20th century.[73][74] For two centuries claims circulated of the discovery of *unseen companions* in orbit around nearby star systems that all were reportedly found using this method,[72] culminating in the prominent 1996 announcement of multiple planets orbiting the nearby star Lalande 21185 by George Gatewood.[75][76] None of these claims survived scrutiny by other astronomers, and the technique fell into disrepute.[77] Unfortunately, the changes in stellar position are so small and atmospheric and systematic distortions so large that even the best ground-based telescopes cannot produce precise enough measurements. All claims of a *planetary companion* of less than 0.1 solar mass, as the mass of the planet, made before 1996 using this method are likely spurious. In 2002, the Hubble Space Telescope did succeed in using astrometry to characterize a previously discovered planet around the star Gliese 876.[78]



Motion of the center of mass (barycenter) of solar system relative to the Sun.

The space-based observatory GAIA will find thousands of planets via astrometry, but prior to the launch of GAIA no planet detected by astrometry had been confirmed.

One potential advantage of the astrometric method is that it is most sensitive to planets with large orbits. This makes it complementary to other methods that are most sensitive to planets with small orbits. However, very long observation times will be required — years, and possibly decades, as planets far enough from their star to allow detection via astrometry also take a long time to complete an orbit.

Planets orbiting around one of the stars in binary systems are more easily detectable as they cause perturbations in the orbits of stars themselves. However, with this method, follow-up observations are needed to determine which star the planet orbits around.

In 2009 the discovery of VB 10b by astrometry was announced. This planetary object was reported to have a mass 7 times that of Jupiter and orbiting the nearby low mass red dwarf star VB 10. If confirmed, this would be the first exoplanet discovered by astrometry of the many that have been claimed through the years.[79][80] However recent radial velocity independent studies rule out the existence of the claimed planet.[81] [82]

In 2010, six binary stars were astrometrically measured. One of the star systems called HD 176051 was found to have a planet with "high confidence" level.[83]

Other possible methods

Transit imaging

An optical/infrared interferometer array doesn't collect as much light as a single telescope of equivalent size but it has the high-resolution of a single telescope the size of the array. For bright stars this resolving power could be used to image a star's surface during a transit event and see the shadow of the planet transiting. This could provide a direct measurement of the planet's angular radius and via parallax its actual radius. This is more accurate than radius estimates based on transit photometry which are dependent on stellar radius estimates which depend on models of star characteristics. Imaging also provides more accurate determination of the inclination than photometry does.[84]

Magnetospheric radio emissions

Radio emissions from magnetospheres could be detected with future radio telescopes. This could enable determination of the rotation rate of a planet which is difficult to detect otherwise.[85]

Auroral radio emissions

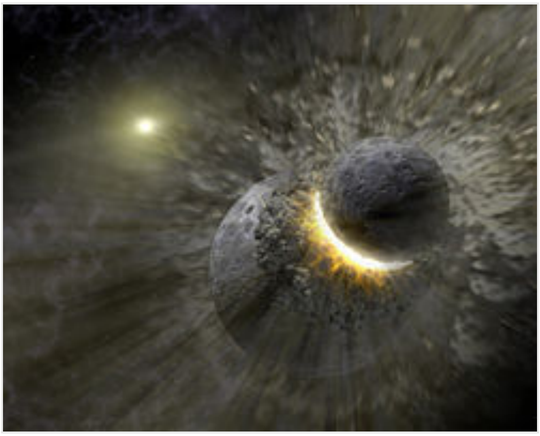
Auroral radio emissions from giant planets with plasma sources such as Jupiter's volcanic moon Io could be detected with radio telescopes such as LOFAR.[86][87]

Modified interferometry

By looking at the wiggles of an interferogram using a Fourier-Transform-Spectrometer, enhanced sensitivity could be obtained in order to detect faint signals from Earth-like planets.[88]

Detection of extrasolar asteroids and debris disks

Circumstellar disks



Disks of space dust (debris disks) surround many stars. The dust can be detected because it absorbs ordinary starlight and re-emits it as infrared radiation. Even if the dust particles have a total mass well less than that of Earth, they can still have a large enough total surface area that they outshine their parent star in infrared wavelengths.[89]

The Hubble Space Telescope is capable of observing dust disks with its NICMOS (Near Infrared Camera and Multi-Object Spectrometer) instrument. Even better images have now been taken by its sister instrument, the Spitzer Space Telescope, and by the European Space Agency's Herschel Space Observatory, which can see far deeper into infrared wavelengths than the Hubble can. Dust disks have now been found around more than 15% of nearby sunlike stars.[90]

The dust is believed to be generated by collisions among comets and asteroids. Radiation pressure from the star will push the dust particles away into interstellar space over a relatively short timescale. Therefore, the detection of dust indicates continual replenishment by new collisions, and provides strong indirect evidence of the presence of small bodies like comets and asteroids that orbit the parent star.[90] For example, the dust disk around the star tau Ceti indicates that that star has a population of objects analogous to our own Solar System's Kuiper Belt, but at least ten times thicker.[89]

More speculatively, features in dust disks sometimes suggest the presence of full-sized planets. Some disks have a central cavity, meaning that they are really ring-shaped. The central cavity may be caused by a planet "clearing out" the dust inside its orbit. Other disks contain clumps that may be caused by the gravitational influence of a planet. Both these kinds of features are present in the dust disk around epsilon Eridani, hinting at the presence of a planet with an orbital radius of around 40 AU (in addition to the inner planet detected through the radial-velocity method).[91] These kinds of planet-disk interactions can be modeled numerically using collisional grooming techniques.[92]

Contamination of stellar atmospheres

Recent spectral analysis of white dwarfs' atmospheres by Spitzer Space Telescope found contamination of heavier elements like magnesium and calcium. These elements cannot originate from the stars' core and it is probable that the contamination comes from asteroids that got too close (within the Roche limit) to these stars by gravitational interaction with larger planets and were torn apart by star's tidal forces. Spitzer data suggests that 1-3% of the white dwarfs has similar contamination.[93]

Space telescopes

Most confirmed extrasolar planets have been found using space-based telescopes (as of 01/2015).[94] Many of the detection methods can work more effectively with space-based telescopes that avoid atmospheric haze and turbulence. COROT and Kepler were space missions dedicated to searching for extrasolar planets. Hubble Space Telescope and MOST have also found or confirmed a few planets. The Gaia mission, launched in December 2013,[95] will use astrometry to determine the true masses of 1000 nearby exoplanets.[96][97] CHEOPS and TESS, to be launched in 2017, and PLATO in 2024[98] will use the transit method.

Primary and secondary detection

Method	Primary	Secondary
Transit	Primary eclipse. Planet passes in front of star.	Secondary eclipse. Star passes in front of planet.

Radial velocity	Radial velocity of star	Radial velocity of planet.[99] This has been done for Tau Boötis b.
Astrometry	Astrometry of star. Position of star moves more for large planets with large orbits.	Astrometry of planet. Color-differential astrometry.[100] Position of planet moves quicker for planets with small orbits. Theoretical method—has been proposed for use for the SPICA spacecraft.

Verification and falsification methods

- Verification by multiplicity[101]
- Transit color signature[102]
- Doppler tomography[103]
- Dynamical stability testing[104]
- Distinguishing between planets and stellar activity[105]
- Transit offset[106]

Characterization methods

- Transmission spectroscopy
- Emission spectroscopy,[107] phase-resolved[108]
- Speckle imaging[109] / Lucky imaging[110] to detect companion stars that the planets could be orbiting instead of the primary star, which would alter planet parameters that are derived from stellar parameters.
- Photoeccentric Effect[111]
- Rossiter–McLaughlin effect

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