The Physical Methods Technique to Detection of Extra-Solar Planets

Khiria Ali Almaghrbi

Tripoli University- Faculty of Education Gaser Ben Ghashir

الخلاصة

تهدف هذه الورقة إلى توضيح بعض الطرق الفيزيائية المستخدمة لاكتشاف كواكب خارج المجموعة الشمسية . يطلق اسم كوكب خارج النظام الشمسي على أي كوكب يوجد خارج نطاق المجموعة الشمسية ، أي كوكب يدور حول نجم آخر غير الشمس ، وقد تم اكتشاف وجود معظم تلك الكواكب بطرق غير مباشرة ، وليس برؤية مباشرة لها لأن قربها من نجم ساطع يجعل رؤيتها بشكل مباشر صعبة جداً ، الأمر الذي أدى إلى تطوير عدداً متنوعاً من التقنيات القادرة على اكتشاف العديد من الكواكب الموجودة خارج نظامنا الشمسي ، ومن هذه الطرق الأساسية المستخدمة لذلك : طريقة عبور كوكب ، طريقة العدسية الصغرية الجذبية ، طريقة زمن النباض ، وطريقة مطيافية دوبلر وتسمى كذلك طريقة السرعة الشعاعية (القطرية). وتعتبر طريقة مطيافية دوبلر (السرعة الشعاعية) الطريقة الأكثر نجاحاً في الكشف عن كواكب خارج المجموعة الشمسية ولا تزال الطريقة الأكثر فعالية.

Abstract

This paper aims to clarify some of the physical methods used to detect extra-solar planets. An exo-planet or extra-solar planets is a planet outside of our solar system that orbits a star. Most of these planets have been discovered indirectly, because their proximity to a bright star makes seeing them directly very difficult. This has led to the development of a variety of technologies that can detect many planets outside our solar system. There are principal techniques which are used: Transit photometry, Gravitational micro-lensing, Pulsar timing and Doppler spectroscopy. Doppler spectroscopy technique is the most successful so far in finding extra-solar planets. It is still the most effective method for detecting exo-planets from Earth.

Introduction

Extra-solar planets or exo-planets are planets orbiting stars other than the Sun. The first detection was confirmed in 1992, with the discovery of planets orbiting the pulsar PSR B1257 +12 (Wolszczan, et al., 1992).

The decades since, astrophysicists and astronomers across the globe have developed an array of methodologies to discover many more of these extra-solar worlds. As these discoveries continue to dominate the scientific headlines and push the limits of observational astronomy, it is important for the non-astro-centric fields of physics to understand the scientific backbone supporting these discoveries (Glaser, 2015).

The first confirmation of an exo-planet orbiting a main-sequence star was made in 1995, when a giant planet was found in a four-day orbit around the nearby star 51 Pegasi. Since the first detection of planets outside the solar system, the number of discovered exo-planets has grown rapidly. To date, more than 1800 exo-planets have been confirmed (Uljan, 2015). The techniques that have been used to accomplish those discoveries and to study the properties of the exo-planets are based on physical phenomena (Lunine, et al., 2009).

The smallest exo-planets are a few times larger than the Earth, and many are several times larger than Jupiter. The fact that most of these planets are so much larger than Earth is thought to be because more massive planets are currently easier to detect than small ones (see ref. [8] http://www.physics.org).

Direct evidence of exoplanets is very difficult to obtain (see ref. [9] http://lasp.colorado.edu). This is because they shine not by their own light, but by light reflected by the star which they orbit. As a consequence, they are much dimmer than their parent star (in the case of Jupiter, for instance, by a factor of 100 billion), and any attempts to detect them by their own light are doomed to failure. Therefore, indirect methods must be used to find extra-solar planets. All of these methods rely on the fact that a planet exerts a small influence on its parent star as it travels around its orbit. By observing changes in the parent star, the existence of the planet can be deduced. Since the changes become larger as the planet becomes more massive, it is always easier to detect Jovian planets than to detect terrestrial ones (see ref. [13] http://www.astro.wisc.edu).

Methods

1. Transit photometry

The transit method for detection of extr-asolar planets is based on the detection of stellar brightness variations, which result from the transit of a planet across a star's disk. This method is also known as the photometric or occultation method (Hans-Jörg, 1998). When a planet passes in front of a star, the planet will block a tiny amount of light. Telescopes can detect this slight dimming and can work out the radius of the planet by how much light is blocked and the orbit by how frequently the planet passes in front of the star. One drawback is that a star needs to have the right orbit so it passes in front of the star . With this method we measure the brightness drop of a star, which results from the transit of one of its planets across its disk (figure1) (Uljan, 2015). This method can determine the radius of a planet, semi-major axis of the planetary orbit and inclination of the orbital plane of the planet. When combined with radial velocity data, a transit can also provide a good estimate of the planet's mass. The orbital period of a planet discovered using transit photometry can be found by measuring the time delay between one eclipse and the next. The principal problem with the transit photometry technique is that it only works for those extra-solar systems which are viewed edge on. Since this configuration is rather unlikely, only a few planets have been discovered using this technique (see ref. [13] http://www.astro.wisc.edu).

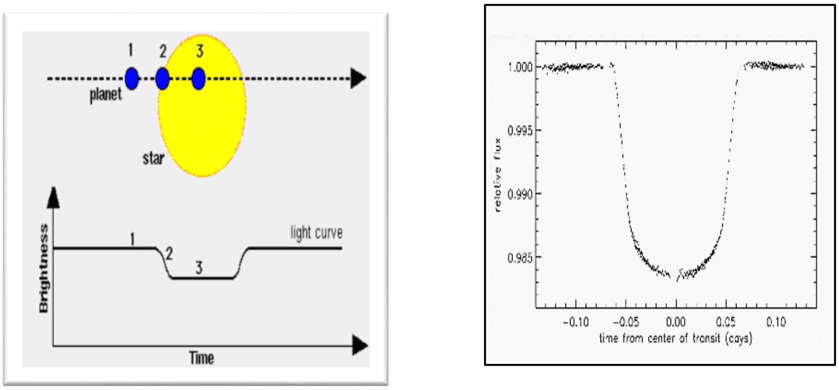

Figure (1): Left: The principles of the transit photometry approach (see ref. [13] http://www.astro.wisc.edu). Right: light curve showing a transit of star HD209458b by its planet (Uljan, 2015).

2. Gravitational micro-lensing

Gravitational lensing is based on the physical phenomenon that light trajectories are bent in gravitational field. Light from the source star ’S’ is bent by the lens star ’L’, so that the observer ’O’ sees the image ’I’ instead of the true source (figure 2). The micro-lensing technique has many advantages. It is more sensitive than other techniques to detect small-mass planets. It is most sensitive to planets in our Galaxy with orbit sizes of a few astronomical units (like those of Mars or Jupiter) (Uljan, 2015).

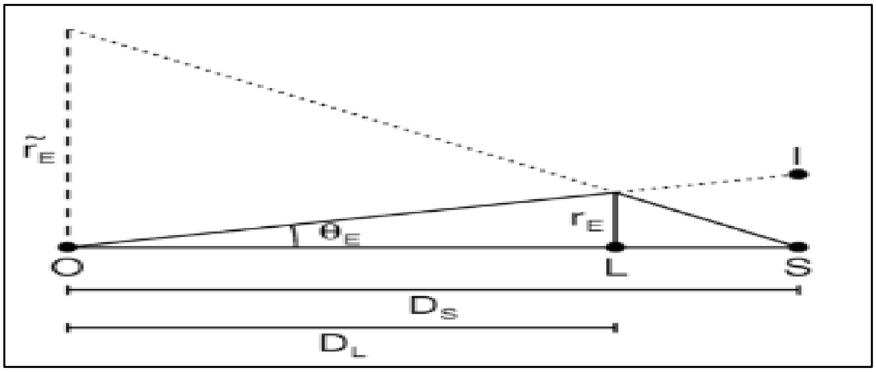

Figure (2): Basic geometry of micro-lensing (Uljan, 2015).

It relies on an effect predicted by Einstein’s General Theory of Relativity: that light rays can be bent by a sufficiently-strong gravitational field. When a planet is orbiting the lensing star, its own gravitational field can contribute to the bending of light rays, and it behaves like a defect in the lens. This defect will produce a narrow spike in the brightness of the lensed star, which can be used to infer the presence of the planet (see ref. [13] http://www.astro.wisc.edu).

If the source star is positioned not just close to the intermediary star when seen from Earth, but precisely behind it, this effect is multiplied (Fig. 3). Light rays from the source star pass on all sides of the intermediary, or "lensing" star, creating what is known as an "Einstein ring" .Even the most powerful Earth-bound telescope cannot resolve the separate images of the source star and the lensing star between them, seeing instead a single giant disk of light, known as the "Einstein disk," where a star had previously been. If a planet is positioned close enough to the lensing star so that it crosses one of the two light streams emanating from the source star, the planet's own gravity bends the light stream and temporarily produces a third image of the source star. When measured from Earth, this effect appears as a temporary spike of brightness Furthermore, the precise characteristics of the micro-lensing light-curve, its intensity and length, tell scientists a great deal about the planet itself. Its total mass, its orbit, and its period can all be deduced with a high degree of accuracy (see ref. [11] http://www.planetary.org).

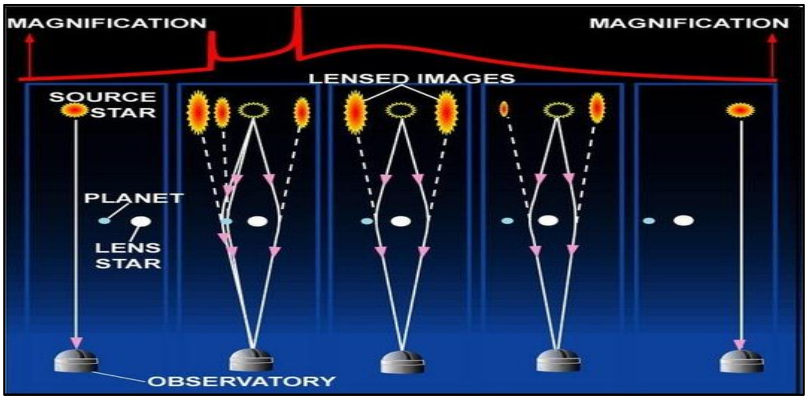

Figure (3): Micro-lensing can reveal exo-planets (see ref. [11] http://www.planetary.org).

3. Pulsar Timing

Pulsar Timing is the method that was used in 1992 by Aleksander Wolszczan and Dale Frail to detect the first confirmed exo-planets (see ref. [12] https://lco.global/spacebook/). A pulsar is a rapidly spinning neutron star with a strong magnetic field. When a planet is introduced, the mutual gravitational pull between it and the pulsar means that they both orbit about their common center of mass (Fig. 4). For two equal-mass objects, the center of mass lies exactly halfway between them; in other situations, the center of mass lies closer to the more-massive object. In the case of a pulsar and a planet, the center of mass will lie very close to the pulsar, since it is much heavier than the planet. Therefore, during one orbit the pulsar will move a much lesser distance than the planet. When the pulsar is moving away from the Earth, the time between each pulse becomes slightly longer; conversely, when the pulsar is moving toward the Earth, the time between pulses becomes slightly shorter (see ref. [13] http://www.astro.wisc.edu).

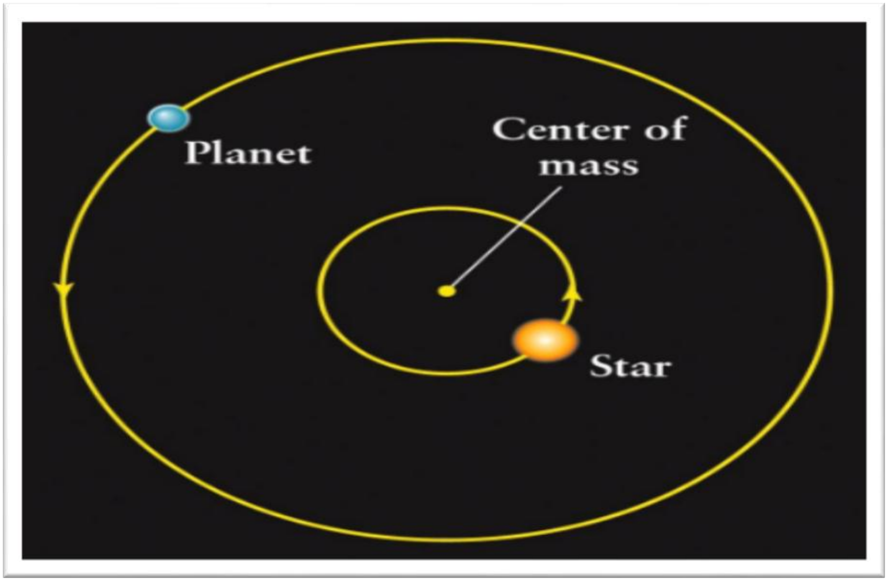

Figure (4) : Shows a star and planet orbiting around their common center of mass (see ref. [13] http://www.astro.wisc.edu).

4. Doppler spectroscopy

The Doppler technique is a good method for discovering exo-planets. It uses the Doppler effect to analyze the motion and properties of the star and planet. The Doppler effect refers to the apparent shift in the wavelength (and frequency) of a wave when there is relative motion between the source of the wave and an observer. The observation of a Doppler shift of the spectral lines of a star indicates a change in the velocity of the star with respect to the observer. When the star moves toward us, the light emitted has a shorter wavelength, so we say its spectrum is blue shifted. When it is moving away from us, the light has a longer wavelength, so we say its spectrum is red shifted (see ref. [9] http://lasp.colorado.edu).

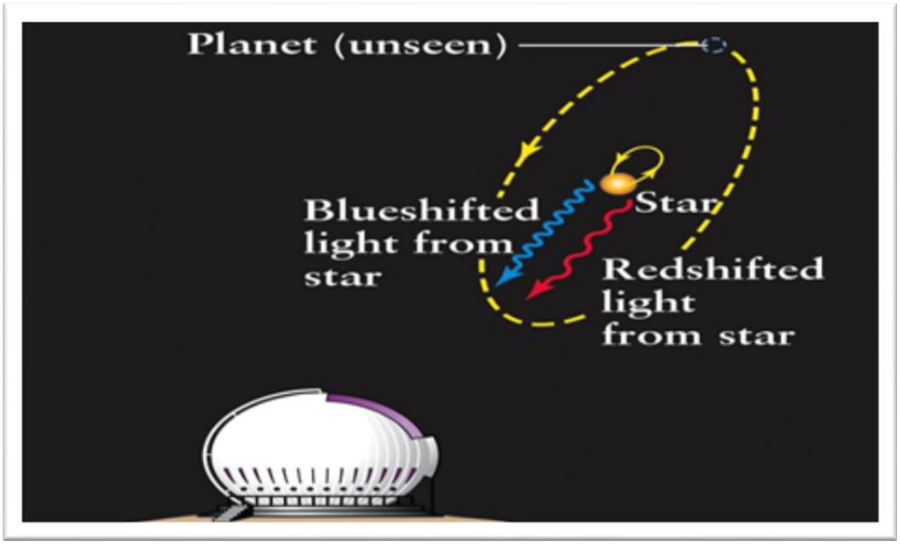

Figure (5) : Shows Doppler shifting (see ref. [13] http://www.astro.wisc.edu).

The radial velocities can be calculated with the aid of the techniques of spectrography and the Doppler effect (Unsoeld et al, 2005):

$$V_r = \mathrm{c}\ \frac{\Delta\lambda}{\lambda_0} = \frac{\lambda - \lambda_0}{\lambda_0}$$

Where:

V_r : The radial velocity

c : The speed of light

$\Delta\lambda$: The wavelength shift of light

λ_0: The wavelength of light

The sign radial velocity is defined: $+V_r$ blue shift and $-V_r$ red shift.

A graph of measured radial velocity versus time will give a characteristic curve (sine curve in the case of a circular orbit) and the amplitude of the curve will allow the minimum mass of the planet to be calculated using the binary mass function. The planet's mass is given by (see ref. [10] https:// lasp.colorado.edu):

$$M_{Planet} = \frac{M_{Star} v_{Star} P_{Planet}}{2\pi a_{Planet}}$$

Figure (6) shows an example of one of the lowest amplitude exo-planets, detected with HARPS. The orbital period for this planet is 58.43 days. The data was comprised of 185 observations spanning 7.5 years (Debra, et al., 2014).

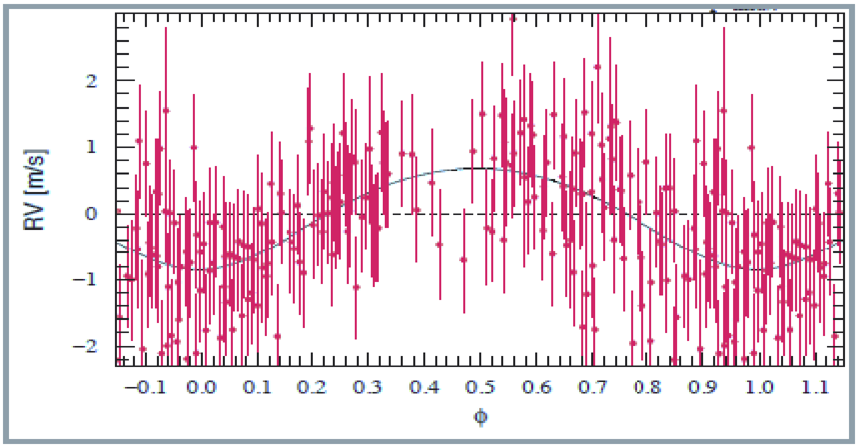

Figure (6) : Shows one of the lowest amplitude exoplanets (Debra, et al., 2014).

Conclusion

Extra-solar planets or exo-planets are planets orbiting stars other than the Sun. Extra-solar planets are incredibly difficult to obtain as the distance of these planets are very much farther from the earth. Hence the indirect techniques were used. All of these methods rely on the fact that a planet exerts a small influence on its parent star as it travels around its orbit. The first confirmation of an exo-planet orbiting a main-sequence star was made in 1995, by Meyor & Queloz, when a giant planet was found in a four-day orbit around the nearby star 51 Pegasi. The discovery was with Doppler spectroscopy method (radial velocities methods).

Beginning with the detection of a planet around the star 51 Pegasi, the Doppler spectroscopy technique has been the most successful so far in finding extra-solar planets, it is best suited to look for very massive planets orbiting close to their parent star.

References

[1]. Debra A. Fischer, Andrew W. Howard, Greg P. Laughlin, Bruce Macintosh, Suvrath M., Johannes Sahlmann, Jennifer C. Yee, Exoplanet Detection Techniques, University of Arizona Press Tucson, 914 pp., p.715-737, (2014).

[2]. Glaser, J. P, 2015, On the Detection of Exoplanets via Radial Velocity Doppler Spectroscopy, Cleveland State University.

[3]. Hans-Jörg D., 1998, Photometric Detection of extrasolar Planets by the Transit Method, On the adress: http://adsbit.harvard.edu//full/1998ASPC..134..216D/0000216.000.html

[4]. Lunine, J. I., Macintosh, B. and Peale, S., 2009, The detection and characterization of exoplanets, Physics Today, May 2009,(page 46-51).

[5]. Uljan, M., 2015, Methods for exoplanet search, University of Ljubljana. Faculty of Mathematics and Physik.

[6]. Unsoeld, A. & Baschek, B., Der neue Kosmos 7. Auflage, Springer-Verlag Berlin Heidelberg New York (2005).

[7]. Wolszczan A. and Frail D. A., 1992, A planetary system around the millisecond pulsar PSR B1257 +12 Nature 355, 145 –147

[8]. A beginners guide to exo-planets, on the address :

http://www.physics.org/article-questions.asp?id=57

[9]. Extrasolar planets, on the address :

http://lasp.colorado.edu/education/outerplanets/exoplanets.php

[10]. Finding masses of extra-solar planets**,** on the address :

https://lasp.colorado.edu/education/outerplanets/math/extrasolar_masses.pdf

[11]. Micro-lensing, on the address :

http://www.planetary.org/explore/space-topics/exoplanets/microlensing .html

[12]. Space Book, 2017, on the address :

https://lco.global/spacebook/pulsar-timing-method/

[13]. The Search for Extra-solar Planets, On the address:

http://www.astro.wisc.edu/~townsend/static.php?ref=diploma-2