Evaluation and Demonstration of the Principle and Results for Different Planet Searching and Detection Schemes

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Abstract. As a matter of fact, exoplanets searching are crucial for human beings for not only searching for new habitats but also for understanding of celestial evolution. In retrospect, the field of exoplanet detection officially initiated in 1992, when the first exoplanet was confirmed to be discovered. Since then, exoplanet searching and detection has become the forefront of astrophysics, allowing scholars to gain information on the life cycle of planetary systems and possibly discover the existence of habitable planet exhibiting signs life form. On this basis, in this article three of the methods will be discussed, including radial velocity, transit photometry, and gravitational microlensing. To be specific, the fundamental principles of which will be explained as well as the state-of-art results will be demonstrated. According to the analysis, the drawbacks or limitations and possible future directions for them will be presented at the same time. Overall, these results offer a guideline for exoplanet searching based on the advanced facilities.

Keywords: Radial velocity; transit photometry; gravitational microlensing.

1. Introduction

Since 1988, when the first suspected scientific detection for exoplanets occurred, the search for exoplanets has come a long way. In the past four decades, a few popular methods for searching exoplanets have come forth, including radial velocity, transit photometry, direct imaging, gravitational microlensing, and astrometry. With the different methods, a total of 5,514 exoplanets was discovered and confirmed in 4,107 planetary systems, including 928 planetary systems that contains more than one planet [1]. The first exoplanet was discovered back in 1988 but it was not confirmed until 1992. In early researches there were a few significant events in exoplanet detection, such as the two Jupiter-mass exoplanets surrounding the second closest stellar system to Earth and closest single star to the Sun, Barnard's star, dis- covered by Van de Kamp through a campaign he launched, however this was later proven false through radial velocity and astrometric work and the exo-planets were found to be nonexistent [2, 3]. Other early discoveries include pulsar planets Poltergeist and Phobetor that orbited the millisecond pulsar PSR 1257+12.

As more than three decades passed since the first exoplanet was confirmed, our technology and ideas have changed, the space telescopes for detection have changed over and over from the earliest of Hubble Space Telescope to the James Webb Telescope now and thousands of exoplanets have been discovered with one of the most recent, HD 36384 b, a super-Jupiter orbiting an M giant star [4]. The current most popular and most successful methods of detection are radial velocity and transit, as the statistics shows that 5,178 out of 5,514 confirmed exoplanets was discovered by them [1]. Furthermore, nowadays in the field of exoplanet searching machine learning slowly emerging. This is because since the last decade, due to more improved technology for telescopes, number of data received are growing at very fast pace, and human are not capable of processing that much data and may produce many errors or could be misled due to varies factor in the data [5].

This study will explore three different types of methods used to detect exoplanets radial velocity, transit and gravitational microlensing. Giving information on how each method operates, the equipment used in order to carry out the different methods and analysis some data obtained through the methods. There will be three sections to the article after this, first being the analysis for each of the three methods of detection. Second being the limitations that is in the current field of exoplanet

detection, and what may be achieved in the future. Lastly, the conclusion, summarizing all the information in the article and giving purpose of this article.

2. Principle and Comparison of Different Methods

In this section, a description of radial velocity, transit and gravitational microlensing is given. Along will the equipment have used and an analysis for the data obtained for each.

2.1. Radial Velocity

Radial velocity is a very popular method in exoplanet detection, with about one fifth of all confirmed exoplanets discovered by it, it is one of the two earliest methods of planet detect alongside timing and was the most used before the invention of transit photometry. This method is favorable for the detection of exoplanets with short period time around their star and has mass similar to Jupiter. The method operates through observation in star movements and the change in their spectral lines. By observing this scientist can see the rate of red- shift or blueshift, allowing the determination of velocity of a star and therefore deduce the presence of a planet around the star [6]. scientist first calculate the rest wavelengths λrest of absorption lines that contains imprinted starlight, then they calculate the observed wavelengths λobs which is the wave- length observed from the absorption lines following the event which caused it to Doppler shift via the star's radial motion. After this point scientists could use the Doppler formula to calculate the relative radial speed between a star and an observatory [7]:

$$z = \frac{\lambda obs - \lambda rest}{\lambda rest} = \frac{1}{\gamma(1 + \mathrm{vr/c})} - 1 \quad (1)$$

Where γ is the relativistic factor, c is the speed of light and v is the scalar relative speed. After confirming an exoplanet using radial velocity scientist can further the investigation using Doppler measurements, they measure the radial re- flex movement of a star in connection to an orbiting exoplanet, which gives the period, distance and shape of an exoplanet's orbit, and therefore providing estimates on the exoplanet's mass [2].

Radial velocity can be detected though the use of telescopes, and the cur- rent State-of-the-art technology used for detection includes "ESPRESSO", "EX- PRES" and "HARPS3" [8]. These equipments are various spectrograph mounted on to the telescope which improves the radial-velocity sensitivity significantly to variation of a minimum of 10 centimeters per second.

2.2. Transit Photometry

Since 2002, when HD209458b, the first exoplanet to ever be discovered using transit photometry, the method has become the most popular and successful in the field, with a total of more than four thousand exoplanets found, it greatly surpassed radial velocity in number of exoplanets detected. With such success, the method is relatively simple, the fundamentals are that as an exoplanet rotates around its host star, periodically, it will pass in front of the host star and align itself between the observer and the star. In that brief period, scientists could observe dimness exhibiting from the star (also known as transit light curve) and deduce the existence of exoplanets. To understand transit, one needs to dive deeper into the transit geometry and study the description of planet transit light curves via the equations given by Seager & Malllén-Ornelas (seen from Fig. 1).

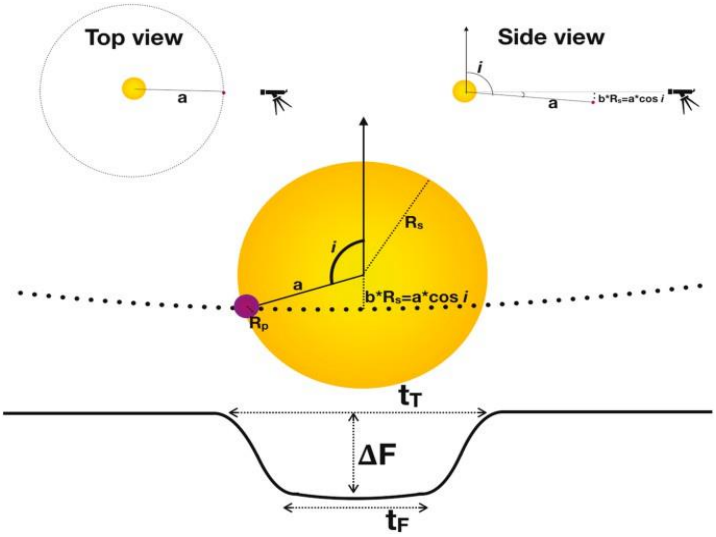


Fig. 1 Transit photometry replication [9].

There are five equations used, first details the calculation of transit depth, measured in ΔF the total observed flux, which is the ratio of a planet's radius and its host star's radius squared [10]:

$$\Delta F \sim \left(\frac{R_p}{R_s}\right)^2 = k^2 \tag{2}$$

Where Rp is the radius of an exoplanet, Rs being the radius of a host star, k, the radius ratio, and F, the flux. This calculation is done to work out the magnitude of an exoplanet given the magnitude of a host star, the magnitude of the host star is deduced from its spectral type. Second equation calculates the transit duration, which as the name implies, is the time it takes for the transit event to occur, this is given as t_T [9]:

$$t_T = \frac{P}{\pi}\arcsin\left(\frac{R_s}{a}\frac{\sqrt{(1+k)^2-\left[\left(\frac{a}{R_s}\right)cosi\right]^2}}{1-\cos^2 i}\right) \tag{3}$$

Third equation calculates the transit shape, also known as transit curve, which is a curve observed as transit event occurs, when the planet passes in front of its host star. This is described by the ratio of the light curve when it is "flat" (t_F), which is when the planet is completely superimposed on to its host star, to the total duration of transit(t_T) [9]:

$$\frac{\sin\frac{t_P\pi}{P}}{\sin t_T\pi/P}\ t_T = \frac{\sqrt{(1-k)^2-\left[\left(\frac{a}{R_s}\right)cosi\right]^2}}{\sqrt{(1+k)^2-\left[\left(\frac{a}{R_s}\right)cosi\right]^2}} \tag{4}$$

Fourth equation is the Kepler's third law, which allows scientists to calculate or estimate a planet's orbit [11]:

$$P^2 = \frac{4\pi^2}{k^2(MSun+MEarth)}a^3 \tag{5}$$

In extra solar cases the equation is derived:

$$P^2 = \frac{4\pi^2}{k^2(MStar+MEarth)}a^3 \tag{6}$$

Where k, the Gaussian gravitational constant used in our solar system is changed to G, the universal gravitational constant and MSun and MEarth (solar mass of Sun and Earth) is changed to Mstar and Mplanet (solar mass of host star and exoplanet). Lastly one would want to know the stellar mass-radius relation which al- lows the calculation of radius of host star Rs:

$$R_s = kM_x^s \tag{7}$$

Where k is a continuous quantity for each stellar sequence and x is the description of power law in each of the sequence. In order to complete transit photometry scientists would ideally want to solve the unknowns of Ms, Rs, a, i and Rp. The method is carried out mostly by space telescopes, e.g., the Kepler space telescope and CoRoT space telescope were both observatories for transiting exoplanets. However, the two telescopes retired few years ago and are since then succeeded the more advanced telescopes, Transiting Exoplanet Survey Satellite (TESS). Characterizing Exoplanet Satellite (CHEOPS) which was launched in one year following TESS to preform follow up observations [12].

2.3. Gravitational Microlensing

Gravitational microlensing or simply microlensing it a subsection of gravitational lensing. It is relatively young in the field of exoplanet detecting, it started popularize at around the same time as imaging, which is a few years after the first use of transit photometry and almost a decade after radial velocity and timing was first use. Although gravitational microlensing is first used not long after transit, but it has no match in terms of popularity and number of planets detect with transit. This is mainly due to the likelihood of the event occurring, the short duration is exhibits and the difficulties in measuring or observing it. Microlensing detects planets though the "direct gravitational perturbation of a background source of light by a foreground planet" [2]. Which means that when scientists detect planets through gravitational microlensing, they would look for a temporary brightness in a star, this is an event that may occur at anytime when two stars are aligned in such a way that the light of a source star (star at the back) bend under the influence of gravitational field of the lens star (star at the front), as shown in Fig. 2, making them look brighter. Once the scientists found the temporary brightness, they could look for the planet orbiting it in a similar way since not only does the gravitational field strengthens the light of the star it also strengthens the light of planets orbiting it [13]. In the general theory of relativity, as light ray from source star moves close to the lens star, it is deflected by an angle. This angle is also known as the "Einstein angle" and is measured as [14]:

$$a = 4GM_L/c^2\xi \tag{8}$$

where G is the universal gravitational constant, the mass of lens star, c the speed of light in vacuum, and ξ the distance from the lens star to one of the light rays as it intersects the lens plane. The basic geometry of gravitational microlensing in single lens (gravitational lensing would have more lenses), in terms of deflection angle, is shown in Fig. 2.

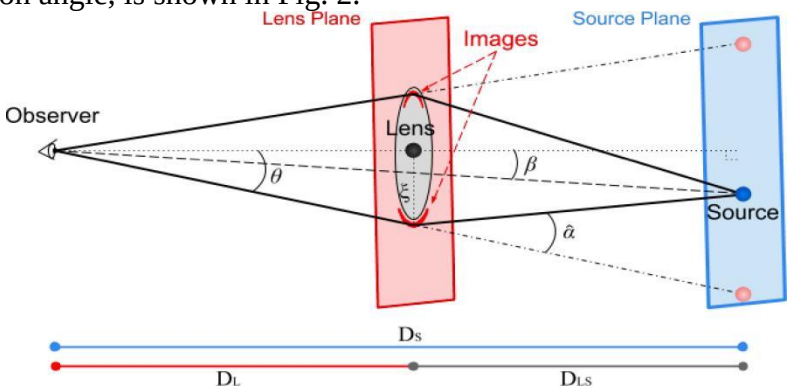


Fig. 2 Replicated geometry for a single lens microlensing event[15].

Seen from Fig. 2, the source plane and the lens plane are parallel, the distance from the observer and lens plane is represented as DL, the distance between the two planes are DLS and the total distance, measured in Ds. Theoretically the observer would be unable to observe the source star itself, but can make out two distorted images shown as the two red spheres on the source plane, the images are the result of the gravitational field of the lens star bending the light. Although theoretically there should be two observed images, but in actual observations, because the two images are so close together, most of the time, on the detectors they appear as one. There are some measurements for the angles of light and image too: ξ is the lens star's distance from the light ray, β is the angle that the

unlensed source is positioned at from the perpendicular line to the two planes crossing the lens star (angular position), αis the deflection angle and θ the angular position of one of the lensed images . Just like all the all the other methods, gravitational microlensing requires the use of telescopes, in the case of microlensing, the Very Large Telescope Interferometer (VLTI) is used, the telescope has a gravity instrument attached which allows the successful resolution of microlensing image.

3. Limitations and Prospects

For every method discussed above, there are drawbacks and things that they just cannot accomplish. In this section, there will be some possible drawbacks of all the methods above and an estimation of what may be the future of planet detection. Radial velocity, this is a method that has a long history, and has been the most successful of a time, but there are just some drawbacks that people cannot ignore [6]:

It cannot determine the mass of planets that are too distant away, but can only provide an estimate, which would be devastating as without an ac- curate mass there is no telling from which category it belongs to or if it is even a planet or not. The problem can be caused by different reasons, e.g., it could be that radial velocity can only observe star spectrum shift when it is blue-shifting or red-shifting from Earth, which means that because the orbital plane is in most cases tilted to some degree, the spectrograph may not detect the full movement, and therefore one could not accurately calculate the masses of planets.

Radial velocity tends to pick up planets that have large sizes and short orbiting periods, which are nicknamed “hot Jupiters”, because exoplanets that have opposite features to this take too long to complete an orbit, making them hard to be picked up by spectroscopy. The downside to this though is that these “hot Jupiters” are generally not habitable, so there would be very unlikely life forms there. Which in our endless pursuit to find life outside our solar system, seems to be bad news.

Transit photometry, this method has provided us with some of the largest sum of exoplanets, but never the less there are still problems with it that bugs people [11]:

The total transit duration is very short, this is a huge problem as a planet may transit for a day or two but then go into orbit for a year or two. This is hugely inconvenient as the method heavily relies on regular observations, and therefore just like radial velocity, it favors the detection of short orbital period planets.

It may give false positives, this could happen at regular intervals because in some cases the size of a star is no different from a planet, resulting in positives given to a star instead of a planet.

Gravitational microlensing, unlike the previous two methods, this method has very little exoplanet count, due to its distinctive limitation [16]:

It can only be observed once, because every microlensing event is unique, and it will never repeat itself due to the movement of stars and expansion of the universe. Which makes it difficult to make calculations for the planet detected.

Because the method heavily relies on the light ray deflected off a gravitational field of a star, it is very hard to accurately determine the distance from which the star is at from the Earth, which poses the problem that if the star is too far away, the uncertainty may be very high.

As mentioned above, this is a method that measures through an event that is extremely rare and could happen at random interval. Which means not only is it hard to look for, scientists also need to know where to look in order to find it.

Most of the limitations discussed above are unlikely to ever be solved because one simply cannot control the way that planets move and when they decide to give out information useful to us. However, in the future of exoplanet searching there is still much one can do, as our technology improves, one could potentially be detecting more exoplanets with higher precision and on smaller scales. Where it will be possible to even detect long orbital period planets or cooler planets that could exhibit traces of life forms.

4. Conclusion

In the past three to four decades since the first detection of an exoplanet was made, the field has grown significantly, with some of the world's most advanced technology aiding its development. It has become the leading field in astronomy, with over five thousand exoplanets found. This article summarized the fundamentals of three exoplanet detection methods, covering the previous most successful method of radial velocity, the currently most successful method of transit photometry, and one of the newest methods of gravitational microlensing. In each method, a brief description of the instruments used to carry out the methods are also included e.g., for transit photometry there is TESS and CHEOPS. At the end of the article, the limitations, drawbacks, and what might be the future of exoplanet searching is discussed. The purpose of writing this article is to study the different methods of exoplanet detection that not only allow the expansion of exoplanet collection but also improve the knowledge on life cycles of exoplanetary systems.

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