# Analysing methods of finding Exoplanets

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***Abstract* - This paper analyzes various methods of detecting exoplanets using various image processing techniques. The paper discusses the underlying physics behind different techniques. There are four main techniques discussed with their characteristics and limitations. Direct imaging relies on infrared imaging of an exoplanet. Microlensing depends upon the apparent change in brightness of the source star due to Gravitational influence. Transit depends upon the dip in brightness of the star due to its planet. Radial velocity method relies on the wobble of a star due to its change in center of mass by an existing planet.**

***Keywords* – Exoplanets, Direct Imaging, Coronagraph, Star shade, Differential Imaging, PynPoint algorithm, Microlensing, General Theory of Relativity, Transit Photometry, Deep Learning, Light curve, Orbital period, Ingress/egress duration, Transit depth, Signal-to-Noise Ratio**

## I. Introduction

Exoplanets are planets revolving around distant stars in the Universe and exploring such planets has been an interesting research area for a lot of scientists and astronomers. Various space agencies and amateur astronomers find exoplanets every year. There are several telescopes in space like the Kepler Space Telescope which is dedicated for finding exoplanets. We are analysing different methods of finding exoplanets. Different methods use different principals of physics and techniques of image processing to determine whether the object observed is an exoplanet or not. This paper gives insights about the methods and techniques used to find exoplanets and challenges in adopting those techniques.

## II. Methods For Detecting Exoplanets

### A. Direct Imaging

Direct imaging method utilizes infrared wavelength properties to capture the reflected light from the observed planet. This is useful because compared to visible wavelength (10^9 time brighter), infrared is only 100 times brighter than Jupiter [1]. As per November 2022 over 200 planets have been discovered using direct imaging method [1]. Conventionally, scientist have been using dark mask called “coronagraph” to cover up the star’s bright glare which can help to detect planet’s faint light. Similar device called “starshade” is also in practice which is positioned as a separate mechanism to block the star light before it enters in a telescope. These general Adaptive optics (AO) system had limitations and failed to detect planets which has less mass and brightness.

Since last decade, advance AO system have been incorporated with sophisticated post-processing method to improve the effect of direct imaging detections which helped in the discovery of atmospheric properties in the detected planet. However, extreme AO has challenges from quasi-statics speckles [1] and to overcome this sensitivity barriers various differential imaging techniques like 1) Angular Differential Imaging (ADI), 2) Spectral Differential Imaging (SDI), 3) Reference Star Differential Imaging have been presented [2]. To improve the image detection and maximizing signal-to-noise(S/N) ratio for speckle structure various algorithms like locally optimised combination of image (LOCI), Karhunen-Loeve Image Projection (KLIP) and PynPoint algorithm have been introduced [3].

### B. Microlensing

Gravitational lensing is a consequence of General Theory of Relativity. Through the gravitational effects on the light emanating from a background star, planets are discovered by Gravitational microlensing. When a lens and the background stars are aligned such that the light from the background star bends under the influence of the lens star, there is a brief change in brightness of the background star [4]. A planet revolving around the lens star too will influence the light of the background star by its gravitational field.

According to General Theory of Relativity, a light ray passing close to a lens of mass $M_L$ at distance $\xi$ will be deflected by the “Einstein angle” [4]:

$$\hat{\alpha} = \frac{4GM}{c^2\xi}, \quad (1)$$

where c is the speed of light in vacuum and G is gravitational constant.

A bright source is at distance $D_S$ from the observer and the lens star is at distance $D_L$ from observer. The angle between true position of the source is $\lambda$ and the angle between optical axis and the image is $\delta$. The relation between all is [4]:

$$\lambda = \delta - \hat{\alpha}\frac{(D_S - D_L)}{D_S}, \tag{2}$$

The surface brightness in gravitational lensing is conserved as there is no absorption or emission. The brightness change of an image is given by the equation [4]:

$$A_{\pm} = \left|\frac{\delta_{\pm}}{\lambda}\frac{d\delta_{\pm}}{d\lambda}\right|, \tag{3}$$

### *C. Transit*

Transit photometry is a technique used by astronomers to discover planets outside of our solar system. This method involves monitoring the dip in brightness of star caused by a transiting planet (passing in front of the star). This is typically done by using a telescope equipped with camera that can capture rapid-fire images of an observed planetary system at a very high frequency. Telescope is pointed towards the star and images are taken for a period continuously. As the transiting planet passes in front of the star, brightness of the image captured by the camera is decreased. This observed phenomenon is analyzed by astronomers to determine the planet's size, its orbital distance from the star and planet's year around the star.

A theoretical light curve model of a transiting exoplanet depicts the following features of an observed planet: transit depth (δ) – providing information of the size (radius) of the planet relative to star, Transit duration (T) – details how fast planet is orbiting the star, Ingress/Egress duration (τ) – describes the time taken to completely cover the star (ingress) and completely uncover the star (egress), and exoplanet's Period (P) – the length of time between two transits is the orbital period, which is the length of planet's year.

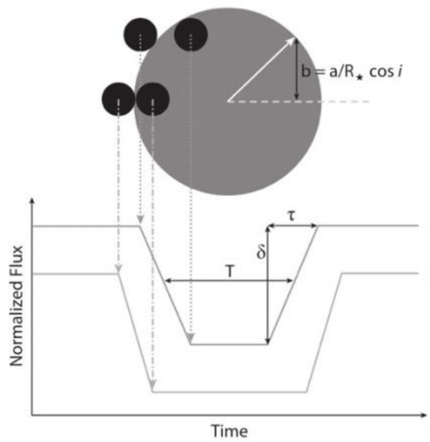


*Figure 1: Theoretical transiting exoplanet light curve [5].*

From these observed quantities, planet radius is calculated from the following relationship,

$$R_P = R_* \sqrt{Transit\ Depth} \tag{4}$$

Where Rp is planet radius, $R_*$ is star radius, and Depth is the relative dip in the normalized flux (observed brightness of star).

Though, several assumptions are made for these observed characteristics. For the simplicity of calculations, star and planet are assumed to be circular, stellar disk is considered uniform, and planet's orbit is assumed to be spherical. Physical parameters of the light curve observed will also vary based on the position of exoplanet relative to the star while transiting. As shown in the figure above, planet of same size transiting at the diameter of star will produce a deeper light curve than transiting planet above the diameter.

### *D. Radial Velocity*

Since 1988, researchers have been using Radial velocity technique to locate planets. Researchers have been able to find a good number of planets using radial velocity. It is also knows as doppler spectroscopy method. It is one of the oldest techniques which has been used for finding exoplanets. This technique searches for exoplanets orbiting stars using stellar wobble, which is the tiny orbit of a star around the star planet's centre of mass [9]. Scientists can predict the period of orbit T and the velocity of the star V. They can also estimate the M which is the Mass of the star and also the inclination of the orbit I.

The velocity of the star V is given by

$$V = \frac{m\sin(I)}{M+m}\sqrt{\left(\frac{G(M+m)}{a}\right)} \tag{5}$$

Here $a$ is the radius of the assumed circular orbit and $m$ is the mass of the planet.

The Period T can be given by Kepler's third law of planetary motion which is as follows:

$$T = \frac{4\pi^2 a^3}{GM_S} \tag{6}$$

Here $M_S$ is the mass of the system given by $M_S = M + m$. Also we can calucalte the orbital radius of the planet by solving the above 2 equations [6].

## III. Distribution Of Exoplanets

The distribution of most of the exoplanets is several 100 kpc from Sun. Radial velocity and Direct Imaging contributes the most for exoplanets findings within several 100 kpc (from Sun). Microlensing is an exception which can find planets even beyond 1000 kpc from Sun.

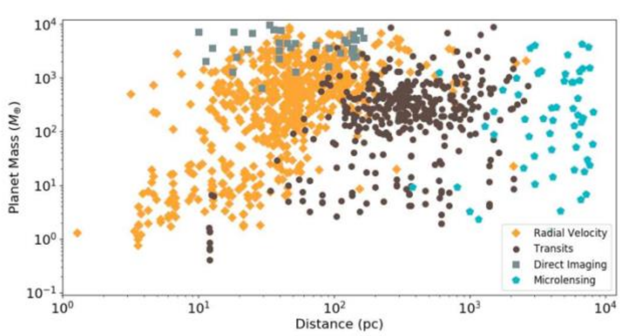


*Figure 2: Distribution of exoplanets (Mass vs Distance from Earth) [4]*

### A. *Direct Imaging*

- Almost all the planets which are detected form directly imaging method are young, massive and shows an extremes of planet formation with masses of > 2 Mj and orbiting in the range of 10 - 250 AU [2].
- Unless indirect techniques, in this method telescopes with 8-10 m class helps the planet detection ranging from 5-10 AU [7].
- Exceptionally large ground-based telescopes of next generation will have angular resolution and sensitivity to directly image planets with $R < 4 R_{\oplus}$ around the nearest stars [3].

### B. *Microlensing*

- Microlensing is sensitive to planets present at distance 1.5 – 4 AU from their host star. This range corresponds to "snow line" where planet formation is most efficient [8].
- Microlensing even detects planets that are ejected by their host stars or due to planet-planet scattering. Such planets do have a gravitational influence due to their mass and hence will not go unnoticed [8].
- Microlensing technique is the only technique that talks about the true distribution of the exoplanetary distribution across universe. Using microlensing, exoplanets as far as 10000 kpc has been found [8].
- Microlensing event is majorly dependent on the planet to host star's mass ratio q. The probability is thus proportional to q. Microlensing till date has found exoplanets with masses ranging from $0.1 M_{\oplus}$ to $17000\ M_{\oplus}$ [8].

### C. *Transit*

- Majority of the planets discovered using Transit photometry are over 100kpc are relatively of larger size and massive. This is partly because smaller planets at this distance do not cause a noticeable dip in brightness of the star.
- Using this technique, the exoplanets with smaller size and mass are only discovered for the planetary systems within 100kpc.
- Transit photometry has been the most popular method used by astronomers and majority of the exoplanet discoveries has been made using this method – There are 3,945 confirmed discovered planets using Transit Photometry [9].

### D. *Radial Velocity*

- Radial Velocity searches around 2003 and 2007 were able to detect velocity variations up to 10 m/s.
- Also the subsequent improvements suggest that we can now observe much higher accuracy of about 3 m/s.
- Radial Velocity is also capable of detecting planets with orbital distance greater that 3 AU [8].

## IV. Usage & Limitation Of Exoplanet Techniques

### A. *Direct Imaging*

As Direct Imaging method is emerging, and new advances have overcome some of the previous challenges there are still some limitations which can hinder the accuracy for detection. It is a useful method when detecting planets visible near the host star. Exoplanets with larger orbits or far from the stars are easy to detect from this method [10]. Also, if exoplanets are not crossing stars, then a direct imaging method is suitable [10]. This method is not suitable for planets which are far away. It is hard to find many exoplanets at once from direct imaging [10]. Situations are challenging for direct imaging method if a star is too bright.

### B. *Microlensing*

Microlensing is unbiased towards lens stars and can well detect planets which are free floating. Microlensing doesn't require extensive resources like large telescopes and has been routinely done by telescopes with aperture of 1 m [8].

Microlensing is a rare phenomenon with a probability of approximately $10^{-8}$ per star. Every year after studying billions of stars, 3-5 planetary microlensing events are observed [5]. Planetary anomalies last for few hours to few days. Microlensing cannot determine the radius of the exoplanet since it is purely based on gravitational influence. Microlensing cannot find planets that are too close to its host star (0.4 AU) or if it is too far from host star (100 AU) [8].

### C. *Transit*

Transit photometry has become a popular method for exoplanet detection due to its high sensitivity and the fact that it does not require high-resolution spectroscopy or direct imaging. Instead, it relies on measuring the changes in brightness of a star over time, which can be done using relatively simple equipment. Another advantage is that it suggests all detected planet's size and orbital periods as well as information of each planet's surface temperatures. Using this method scientists have discovered that there are seven planets revolving around the nearby dwarf star, TRAPPIST-1, that have similar masses and sizes as earth [11].

However, there are some limitations of this technique that the observed planet's orbit needs to be aligned from Earth [11]. Information collected with technique can be of limited accuracy due to astronomical activities and instrument noise. There can also be false positives due to external factors such as a passing comet or a binary star system which may cause the periodic dip in brightness as well.

To address these difficulties, some of the researchers have initiated the use of deep learning, a machine learning algorithm class, to detect and analyze exoplanet transits autonomously which will help improve this method's efficiency and accuracy [12].

### D. *Radial Velocity*

Over the years there have been many improvements in detecting exoplanets using the radial velocity technique but there are still a few drawbacks. It is impossible to simultaneously detect a huge number of stars with just one telescope, but this can be done using other techniques. This technique also sometimes can generate false positives in case of a multi-star system [6].

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