Analysis and Comparison for Scenarios of Detection Exoplanets

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Abstract: As a matter of fact, detections of exoplanets are always important for cosmology observation. With this in mind, this study focuses on the introduction of different exoplanets detection method and comparison between these methods. To be specific, three scenarios, i.e., radial velocity method, transit and astrometry method, are introduced. In fact, radial velocity method makes use of the redshift of absorption lines. At the same time, transit detects the periodic variation of intensity of host stars. Differently, astrometry focuses on the slight change in position of host star in the sky. Based on the evaluations, Radial velocity method has high accuracy but large scaled equipment. According to the analysis, transit is the most popular method and astrometry is least welcomed due high precision needed. Overall, these results provide a guideline for researchers to choose appropriate exoplanet detection method as well as shed light on guiding further exploration of exoplanet searching.

1 INTRODUCTION

Exoplanet is an old and popular topic in the history. It was first suggested ancient Greek people. In modern history of astronomy and physics, Giordano Bruno was the first person to declaring this concept, in his book called "De L'Infinito, Universo E Mondi". Isaak Newton also mentioned this concept in the book "Philosophiae Naturalis Principia Mathematica". Exoplanet region is very popular that occupying 3 to 4 percent of all papers in astronomy (Parthasarathy, et al., 2025). Meanwhile, large amounts of missions and projects are related to exoplanet area such as TESS. This popularity is not surprising due to the meaning and purpose of doing research on exoplanet. The first aim is to find aliens or creatures away from earth (Lee, et al., 2012). On the ground of current studies, lives similar to human beings are more likely to live in planets rather than stars. Secondly, finding exoplanet helps to find the possible destination for human's space travel. It is essential for human to find an exoplanet with similar condition to earth allowing human to live without large adjustment. Thirdly, learning exoplanet can improve the knowledge to solar system. Evaluating different star system can provide a better vision and model of principles of star system. This enables further prediction the solar system.

Different method was applied to determine exoplanets in the history. In reinvent years, satellite provide a huge improvement on finding exoplanets, because they can provide full-frame image with higher precision and clarity (Ricker, et al., 2015). This is because they are not affected by the atmosphere. Kepler mission and Transiting Exoplanet Survey Satellite (TESS) provide a lot more raw data and identify a large number of exoplanets. They found these stars by mostly transit and radial velocity methods. Kepler and TESS also reveal more theory behind exoplanets based on their observational results. This includes astrochemistry, other features of the planet (e.g., radius, age and mass). For instance, the composition of star was widely learned and researched in recent papers. Astrogeodetic measurements are also implemented in newer researches. This astrogeodetic analysis helps researcher to build a more precise astrometry model. Meanwhile, new and upcoming missions like PLATO are likely to provide a more precise and scoped vision to exoplanets (Deeg, 2024).

This research aims to provide a clear introduction to current methods on detecting exoplanets and make comparison between these methods to figure out the limitations and advantages of each method (Sekhar, et al., 2025). The first chapter will give an overview of common methods in determining exoplanets. The second chapter will about the radial velocity method.

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This chapter will focus on the principle, the main equipment of this method and the observational outcomes by this method. The third part will introduce the second method which is transit. This Section will follow the same structure as the second section. Thus, the third chapter will cover principles, equipment and observation too. The fourth section is going to be about astrometry. This method is relatively not that popular and have less results due to the lack of precision of detection. The first determined planet was just found in 2013. However, as the development of scientific equipment and methodology, astrometry becomes increasingly welcomed by astronomers. In this paper, fourth chapter will have the same structure as previous two. The fifth chapter is about the comparison between these three methods and prospects. Lastly, the sixth chapter is conclusion.

2 DESCRIPTIONS

Radial velocity method is a common method in detecting exoplanets. It detects the redshifts of planets and calculate the radial velocity by Doppler effects. Through this analysis, the presence, the orbit and the mass of exoplanets can be determined. Transit is another method of detecting exoplanets. This method traces the intensity of host stars. If there is a periodic decrease in intensity, this indicates the presence of a planets which will transmit the star. By analysing the length of decreased intensity, the size and the orbit of the exoplanets can be measured. Astrometry uses precise comparison of position to detect the presence of exoplanets. The host star will have slight movement in the sky by measuring the distance between other stars, the position can be measured to see whether a change in position occur. The orbit and the mass of the planets can also be calculated by the amount of position change of the host stars. Direct imaging is a straight forward method of determining an exoplanet. A single pixel of the image may be considered as a noise, but a continuous images of an orbiting light spot can illustrate the presence of an exoplanet. Thus this needs continued observation and only work for large planets which emits noticeable light and far enough from the host stars. Gravitational microlensing has a relative complicating mechanism. Due to relativity, the planets will bend the space around it, this causes the light travelled passed by or near this planet to bend into a different direction, scientists can determine this bend and figure out the presence of exoplanets. In other words, the image seen from human vision varies from the actual location of stars in 3 dimensions.

3 RADIAL VELOCITY

This method is based on the principle of Doppler's effect. Doppler effect is a traditional principle in classical physics. It claims that the wavelength observed by the observer depends on the relative speed between the source and the object and the original wavelength. The formula is shown bellowed.

$$\lambda' = \lambda\left(1 + \frac{v_r}{c}\right) \tag{1}$$

However, in astronomy, scientists more often to obtain the observed wavelength and the origin wavelength, thus they want to figure out the radial velocity of this object. This is because astronomers use Doppler's effect in the context of spectroscopy. In spectroscopy, the redshifts are measured on these absorption or emission lines rather than a pure light. Therefore, it is easy to figure out the original wavelength where scientists can obtain this wavelength from the laboratory. As a result, the formula will vary in the from as shown followed:

$$v_r = c\left(\frac{\lambda' - \lambda}{\lambda}\right) \tag{2}$$

Besides the theory part, the reality shows far more complexity. This mainly includes two stages, light obtains and fit.

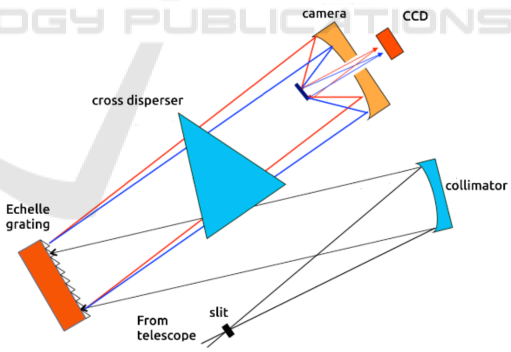

Figure 1: The layout of Echelle spectrograph (Trifon, 2024).

The precision of the spectroscopy is low in early stages. Thanks to the method of Échelle spectrograph, the precision of spectroscopy has dramatically increased (Trifon, 2024). The Fig. 1 shows the mechanism of Échelle spectrograph. It splits the light into blocks enabling more precise results of detection of absorption lines. The light will first pass through an image slicer which will split the beam into several narrower beams. This can increase the efficiency and resolution of the image. The light will then pass through a collimator. Collimator is a mirror with same focus as the telescope. Thus, the collimator will spread the EM waves into parallel beams. After that the beams will reflected by the Échelle grating. This grating will have small grating constant and large incidence angles. This helps the waves have more overlapping wavelength intervals in the edge of the image. As these overlapping wavelengths are not useful as the single one, this action makes the image contain more information and easier to interpret. Lastly, the light will enter the cross disperser and be focused by the camera's CCD or CMOS. In conclusion, this equipment, Échelle spectrograph, provide benefits including high spectral resolution, large wavelength coverage, compact design and versatility.

Fitting is also a difficult part, because the signals can submerge in the sea of noise and change shape due to other interference. Apart from increasing the resolution of CCD to increase the signal-to-noise ratio (SNR), how to enhance the stability of the instrument is also vital. Here comes to one method to overcome these unstable factors that can lead to failure of detection, which is the I2 cell method.

This method introduces an iodine gas cell into the path of the beam (Trifon, 2024). This process allows the absorption lines of the stars detected to superimpose with the absorption lines of I2. Thus, the absorption feature and shifts are more stable, due to the presence of easily identified reference lines of I2. It was implemented in HIRES spectrograph (Lizzana, et al., 2024). This equipment achieving the precision down to 3ms-1. The advantages of this method are obvious. Firstly, it is inexpensive to settle, but it stills provide a high resolution. Meanwhile, the small size, maintenance cost and ease of use are all benefits related. There are also some drawbacks of it like extraction process is complicated. However other methods like simultaneous Th-Ar calibration method can have the same effects.

4 TRANSIT

Transit is also a common method of detecting exoplanets. In recent studies, codes and computer are also used to determine the probability of transit. For instance, python code lightcurves can be used to model and analyze the light curves. This python code package makes use of the project "Exolock Project". (Bass and Daniel, 2024) This module helps to determine the parameter including the mass of host star, orbit radius, mass of the exoplanet, radius of the exoplanet and the density of the star. In this module, many data of specific exoplanets are stored and used as the historical data. After this an analysis should be carried out to fit the rotation of the exoplanets. The first model can be applied is linear model. This model assumes the planets has a circular orbit and a constant orbiting speed. Thus, the equation to this model can be expressed as followed:

$$T_d^c(E) = T_{d0} + EP_d + \frac{dP_d}{2dE}E^2 \quad (3)$$

In the equation, T_{d0} is the mid-transit time while P_d is the orbital speed. E represents the epoch number round to the closet integer. As a result, a mid-transit time is obtained by fitting this model. Monte Carlo Markov Chain sampler is applied to fit this linear model. The second model can be used is Orbital Decay model. This model also assumes a circular orbit. However, it has better complexity. Unlike the first model, the orbital decay model assumes a changeable speed with steady changing rate. This allows the equation to be obtained as followed.

$$Q'_* = -\frac{27}{2}\pi\left(\frac{M_p}{M_*}\right)\left(\frac{a}{R_*}\right)^{-5}\left(\frac{dP_d}{dE}\right)^{-1}P \quad (4)$$

Here, P_d is the orbital period and dPd/dE is the rate of change in orbital period in each orbit. The Monte Carlo Markov Chain sampler can also be applied to fit this model with the actual data. While using transit method, the tidal quality can relatively easy to be obtained. (Wallace, et al., 2025) Applying some translation of the formula the function can be obtained as shown bellowed. The third model is Apsidal model. This model assumes the orbit as an eccentric orbit. The argument of this orbit of its pericenter will precessing uniformly over the time. From Gimenez and Bastero's research the mechanism of this apsidal model is gained as the equation shown.

$$T_{ap}^c(E) = T_{ap0} + P_sE - \frac{eP_s\cos\left(\omega_0 + \frac{Ed\omega}{dE}\right)}{\pi(1 - \frac{d\omega}{2\pi}dE)} \quad (5)$$

Here, T_{ap0} is the reference time and the e is the eccentricity. W is the argument of the pericenter. Ps is the sideral period and dw/dE is the rate of change in orbital period in each orbit.

5 ASTROMETRY

Astrometry method includes a precise mathematical modeling to the motion of the stars and hence to calculate the period and other features of the host stars. The direction or the angle between the host star system and earth is vital, as this will influence the direction vector it seperates. In other words, the radial velocity method considers the radial velocity while the astrometry considers the tangential velocity. In the most extreme examples, the star system which has a planar normal to the vision from earth cannot be determined by the radial velocity method, and the star system parallel to solar system cannot be measured by the astrometry method. However, radial velocity method is still more popular as the shifts of the absorption lines are easier to be determined than the motion of several pixels in the image (Simon, et al., 2025). To model the motion of the star, the motion is considered as a periodic movement due to the Newton's law of gravity. Scientist often use trigonometric functions to express the motion in polar coordinates forms (or can be said in complex numbers forms) (Simon, et al., 2025). The equation is expressed as followed:

$$Rx = Rcos\omega t \text{ and } Ry = Rsin\ \omega t \quad (6)$$

In the equation, R is the wobble radius of the host star from the barycenter. Combined these tow equations, a new 2 dimensions expression is derived as followed.

$$E(\rho,\theta) = (\sqrt{2})^{|l|}\left(\frac{\rho}{\omega_0}\right)^{|l|}\exp\left\{-\frac{[(\rho cos\theta - Rcos\omega t)+(\rho sin\theta - Rsin\omega t)]}{\omega_0^2} + il\Phi\right\} \quad (7)$$

Secondly, the light will pass through a vortex filter. This will give an additional phase of the original light separated from the whole expression as shown in the combined equation. Then the left and right quadrants are split and their difference are seen. The equation is given as:

$$I(\rho,\theta) = 2^l\left(\frac{\rho}{\omega_0}\right)^{2l}\exp\left[-\frac{2(\rho^2+R^2)}{\omega_0^2} + \frac{4\rho R}{\omega_0^2}cos(\theta - \omega t)\right] \quad (8)$$

The denominator is the radial coordinates of the host star from the vortex filter or detectors, whereas the θ is the angle between the center of the detector and the Gaussian beam. This difference is then normalized. The purpose of this normalization is to totaling the difference in the intensity of the left side and the right side. The equation is shown as followed.

$$\Delta I_{norm} = \frac{I_{right} - I_{left}}{I_{tot}} = \frac{I\left(\rho,-\frac{\pi}{2}\leq\Theta\leq\frac{\pi}{2}\right) - I\left(\rho,\frac{\pi}{2}\leq\Theta\leq\frac{3\pi}{2}\right)}{I(\rho,\Theta)} \quad (9)$$

To simplify the calculation, the value of the equation 2 is substituted into equation 1. The new equation one obtained is like followed. Thus, an equation of the difference in intensity in the form of a polar equation is obtained and is ready to be visualized. Finally, by taking a Fourier transform, the equation can be expressed in the form of summation. The equation is in the form as shown below:

$$\Delta I_{norm} = \Sigma_{n\ odd}\frac{(-1)^{\frac{n-1}{2}}2^{\frac{n+2}{2}}\beta^n\Gamma\left(\frac{2l+2+n}{2}\right)_1F_1\left(\frac{2l+2+n}{2};n+1;2\beta^2\right)\cos(n\omega t)}{n\pi\Gamma(n+1)\Gamma(l+1)_1F_1(l+1;1;2\beta^2)} \quad (10)$$

When plotting the figures, a trend of dominating terms can be seen (seen from Fig. 2). In conclusion, a series of mathematical techniques are applied here to implement to explores the motion or detectors the motion in a precise way.

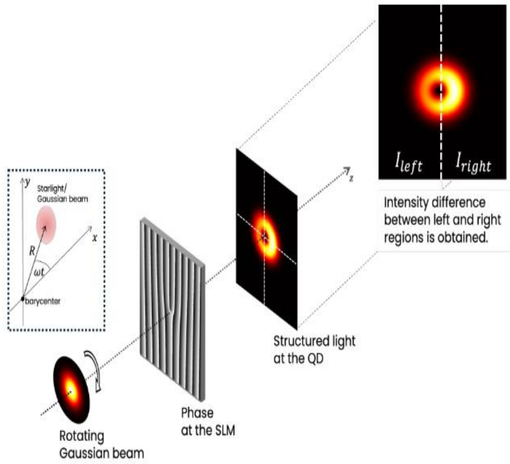

Figure 2: The mechanism of vortex filter (Simon, et al., 2025).

6 COMPARISONS

Based on the previous research and introduction. The advantages and disadvantages are clear and obvious. Firstly, the benefits and drawbacks of radial velocity method. Radial velocity method is the obvious most straight forward metho. It makes use of the absorption and emitting light lines. Thus, the shift of the absorption line can be used to determine the radial velocity and hence find the period and radius of the exoplanet. This feature gives radial velocity method a high accuracy due to precision of absorption lines in comparison to other detection like intensity or position. Meanwhile, the ease of applying radial velocity method is also outstanding. Unlike, other methods nowadays have a high reliance on computer simulation and modeling. Radial velocity method relies on computer in a very slight amount. For instance, it does not need to fit with a model to get the result. At the same time, it does not require a prediction of the data or first step analysis on whether this host star experience an epoch or motion. However, this method needs large and complex equipment this paper has mentioned before like I2 container. This restricts the size of the Telescope and limit the devices on ground level. These complex devices will furtherly cause high start-up and maintenance cost and ask for higher level of researchers that are able to understand the mechanism behind these devices (Zakhozhay, et al., 2022).

For transit and astrometry, they have quite similar trend of benefits and drawbacks. However, transit is a lot more popular than astrometry due to its more obvious phenomenon. They both require a continuous detection. And the duration of the observation depends on the period of the exoplanets. This gives more uncertainty In the observation. In difference, transit requires the detection of intensity. Thus, the intensity is easier to model and detect the change of them. This also allows the telescope to be brought to space like Kepler and TESS.

However, this paper only mainly focuses on the theory and mechanism part. It covers a limited number of actual results. For the future, a more precise comparison can be made based on the observational results.

7 CONCLUSIONS

To sum up, this study gives a brief introduction on three different methods on how to detecting exoplanets. They are radial velocity, transit and astrometry. A comparison also be made to give their advantages and disadvantages. The introduction mainly focuses on the mechanism and tools used in detection. The comparison gives reasons and feature on their benefits and drawbacks. In the future, it will be beneficial to overcome these drawbacks and reach a higher resolution. This allows more accurate understanding on exoplanets. This paper concludes the mechanism of these three methods including radial velocity, and figure out the limitation of current method.

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