Analysis Of the Exoplanet Searching Based on Transit and Radial Velocity Method

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Abstract. Exoplanet searching is one of the most important themes in astrophysics and astronomy. There have been countless missions aiming to find planets out of the solar system, and further on to find extraterrestrial life. This study is an analysis on the different exoplanet detection methods, by their usage on detecting certain major properties of exoplanets. The two most used methods, namely transit method and radial velocity (RV) method, would be evaluated using frequency of usage with exoplanet.eu as the data source. According to the analysis, transit method exceeds in determining planetary radius, temperature, and geometric albedo, while RV method is not useful to determine these properties. RV method is very useful in determining planetary mass and orbital eccentricity, yet transit method is not as useful for these properties. The two methods are both moderate in detecting orbital period and semi-major axis (RV method is slightly more useful in determining semi-major axis). Both methods are not so useful at determining inclination out of the near-90 degree range. Geometric albedo is rarely confirmed, so whether which method, limited detection was made. These results provided some insight into which detection method to utilize/search for when trying to find specific data about certain properties. It might be useful as a guide to fellow students and amateur astronomers on exoplanet detection methods.

Keywords: Exoplanet searching; exoplanet detection method; transit method; radial velocity method.

1. Introduction

Exoplanet exploration is one of the most important themes in nowadays astrophysics and astronomy. Understanding exoplanets may provide insight into understanding our own solar system. Moreover, acquiring information about exoplanets would help one of the biggest questions humans ever had whether there life elsewhere. Nevertheless, exoplanets need to be detected before doing research about them, and that proofed to be a challenge. Exoplanets, as its name suggests, are planets out of our solar system. These systems are usually very far away from Earth, so direct imaging can provide a very limited amount of data. Therefore, the theme started to prosper late, and since then there has been countless missions and projects aiming for exoplanets.

The first exoplanet was discovered in January 1992 [1]. Since then, a lot of missions have been launched across the globe to find more exoplanets. These missions are mainly based on space telescopes, as they are not disturbed by Earth atmosphere like ground-based telescopes. Launched in 2003, NASA's Spitzer Space Telescope was "the first telescope to directly detect light of planets outside of our Solar System", it uses infrared to detect exoplanets [2, 3]. In 2006, ESA's COROT mission became "the first mission capable of detecting rocky planets" [4]. A more specified mission called Kepler, designed specifically for detecting exoplanets, carried out in March 6, 2009. The Kepler was "NASA's first planet-hunting mission", with an extended mission of K2 [5]. More recently in 2018, NASA launched another mission specified on exoplanet detection named TESS, led by MIT [6]. Over the years, thousands of exoplanets have been confirmed and classified, into terrestrial planets (Earth-like), "super-Earths" (more massive rocky planets), "Neptunes" (ice giants) and other giants (Jupiters and Hot Jupiters), etc. [7].

There are many approaches to detect exoplanets. Namely, the two major methods of radial velocity (RV) method and the transit (primary transit and secondary transit) method, along with other methods such as astrometry, microlensing, direct imaging. RV method involves the Doppler effect, in which a star would appear to be red when moving away from the observer, and blue when moving toward the observer. The planets orbiting the star would pull the star into a circular orbit, causing the star to wobble, thus changing the star's light from red to blue alternatively. Astronomers would then measure this color change, or the "Redshift", using it to find the radial velocity of the planets orbiting the star, and further on to other properties [8]. Transit method involves the measurement of a star and its surrounding's brightness. When a planet goes in front of the star it blocks some of the light, reducing the brightness data observed, or it may also increase the brightness data observed by reflecting the star's light. By measuring the brightness, astronomers can acquire some properties of the planet's orbit. Transit method contributes to most of the exoplanet discoveries to date [9]. Beside these two major methods, astrometry, microlensing, and direct imaging also helps with exoplanet detection. Astrometry is "the measurement of a star's position relative to the background sky", it is the direct measurement of a star's wobble caused by orbiting planets [10]. However, usually the star's wobble is too small to measure, so this method could detect very limited number of exoplanets. Microlensing is the use of the gravitational lensing effect of celestial bodies. Celestial bodies bend light at a visible magnitude on its surroundings, and occasionally a star would get near this area and its light would be bent. Astronomers can observe this bent, and if planets were near this star, perturbation would have a visible effect on the bent light, and thus the planet can be detected [10]. This method is able to detect planets as light as "few times the mass of the Moon", and is able to detect rogue planets, or planets that didn't go into a orbit, because the planets itself can have some microlensing effect as well, but it required a microlensing event [11]. At last, if the planet is close and big enough, direct imaging by visible light can also be done.

This paper would mainly focus on the RV method and transit method. The topic of exoplanet is quite popular in recent years, which is one reason this paper is written. Another motivation, which is the major reason, is the interest in the question of which major exoplanet detection method to use in determining different planet properties. This can be shown in the reverse way, finding the advantages and disadvantages in the RV method and transit method, resulting in this paper. For the remainder of the paper, the data and models used would first be explained. Then, using the data and model, a calculation and investigation would be done to analysis the two methods. At last, limitations would be explained, and future outlooks would be suggested, with a short conclusion in the end.

2. Data and Method

2.1. Data

The data used in this paper are from exoplanet.eu, Encyclopaedia of Exoplanetary Systems. This is a website of confirmed and unconfirmed exoplanet discovered worldwide, verified by the European Union [12]. The website has mainly two parts, namely "Catalog" and "Plots". The "Catalog" sector is basically a frequently updated database of the exoplanets [13]. The "Plots" extracts information from the database and use it to plot scatter points graph, histogram, or a kind of polar graph [14]. For this paper, the histogram graphing function would be utilized. The website could plot the graph according to status (confirmed or not), detection methods, and two variables of choice (planetary mass, year of discovery, etc.) [14]. Besides, the graphing tool has a choice of whether to build a cumulative graph or not (cumulative graphs add all the values before to the value at one place, meaning that the value would always increase along the x-axis until reaching maximum) [14]. Also, some parts of the paper would utilize information directly from the "Catalog" section, as special or representative examples for evaluating detection methods.

2.2. Models

The models used in this paper are basically the calculation formulas of certain planet properties, particularly the ones calculated by detection of transit method or RV method. There are a lot of properties that could be found out by calculation from the result of using the detection methods, but only the major ones would be evaluated in this paper. The major ones include planetary mass (M), planetary radius (R), orbital period (P), orbital eccentricity (e), orbital inclination (i), temperature (T), geometric albedo (no agreed symbol), and semi-major axis (a). For transit method, the results from observation are brightness data at different given time. This is caused by the planet being on different phases of the orbit at different time period. When the planet goes directly in between the observer and the star, it would block some of the star's light, reducing the brightness observed, this is called the primary transit. However, the planet actually reflects some of the star's light according to its albedo (reflection rate), so it would increase her brightness data observed by a little amount according to the proportion of its day side observed. In other words, when on the half of orbit closer to the observer, it would increase the brightness by a little, and on the other half, a little more. At last, if the planet goes directly on the extended line from the observer to the star, it will get blocked by the star and stop increasing the brightness data observed, this is called the secondary transit. For this paper, since planets discovered by the transit method always come with both primary transit and secondary transit, they would not be distinguished. The core formula for the transit method is the following (the change in light observed, "ΔFs", is related to the relative surface areas of the planet and star):

$$\frac{\Delta F_s}{F_s} = (\frac{R_{planet}}{R_{star}})^2 \tag{1}$$

For RV method, the data observed are the Redshift of the starlight's Doppler effect. Redshift is the amount for which the star's light (emission spectrum) moves to the red side (if it is negative, it becomes blue). For a star, if a planet is orbiting it, they would orbit each other around a center point, the center of gravity. Thus, unless if the orbital lane is directly perpendicular to the observer (in which the orbital inclination, or the angle between the orbital plane's normal to the line of sight, would be 0° or 180°), the star would move away from the observer and back again periodically. The speed at which the star moves away/to the observer is called the radial velocity, which, combined with other data could reveal some properties about the planet. The core formula for the RV method is radial velocity in relation with other properties:

$$V_r = -K\sin(\omega t) \tag{2}$$

In which "ω" is the angular velocity, and "K" is a constant for the star that could be deduced from:

$$K = (\frac{2\pi G}{P})^{1/3}\frac{M_{planet}}{{M_{star}}^{2/3}}\sin(i) \tag{3}$$

3. Results and Discussion

3.1. Transit

The usage of transit method over the years was staggering among all other exoplanet detection method. In total, 3892 exoplanet discoveries were made by the transit method, out of the 5641 confirmed exoplanets [13]. It is therefore safe to conclude that this is most frequently used method of exoplanet detection. By analyzing its usage in determining planetary mass and radius, orbital period, eccentricity and inclination, temperature, geometric albedo, and semi-major axis of exoplanets, its advantage (and disadvantage) in detecting certain properties could be shown. The first topic is planetary mass. The number of planets' planetary mass detected by transit method is 1374, out of the total 3101 [14]. This number did not even reach half (percentage about 44.3%), which shows that transit method are not so often used in detection of planets' mass. This may be because brightness data relies on the surface areas of the planet and the star, so the raw data from observation (brightness) could only be used to figure out the surface area. There is a way to calculate the mass this way, which is to find the volume of the planet and use its density, but density is something that required multiple detection approaches to calculate.

The number of planetary radius detected by transit method is 3847, which is the dominating majority in the 4029 discoveries (percentage about 95.5%) [14]. This is not surprising, as the planetary radius is directly related to its surface area (idealizing the planet as a sphere), which is directly related with the brightness data observed. By using the raw brightness data (reprocessed into vertical sector of the surface area) and the surface area formula ($S=4\pi r^2$), the radius could be directly calculated.

Transit method detection of orbital period is 3884, about 75.7% out of the total 5132 [14]. This appears to be a majority, which implies that the transit method may be a decent way to detect the orbital period, but the data is not significant enough to form definite results. The reason behind this couldn't be solved simply by mathematics (maybe it had some connection with the orbital radius, which may have an negligible influence on the light blocked by the planet). For orbital eccentricity, another important property of an orbit, transit method made 1201 discoveries, out of the 2344 total, which is about half (percentage about 51.2%) [14]. Considering how frequently transit method is used, this number was a bit low. This may be because orbital eccentricity has nothing that relates directly to surface area of planets, so the brightness data observed couldn't be used to determine the orbital inclination. Orbital inclination is an interesting property considering transit method. Orbital inclination discovered by transit method is 1502, out of the total 1678 (percentage about 89.5%), which is a dominating majority [14]. This is not surprising as using the method itself revealed something about the orbital inclination. Specifically, since a transit could happen only when a planet is between the star and the observer, the orbital inclination could only be around 90 degrees (seen from Fig. 1). It could be observed that the majority of discoveries are near the "90" degree section, the majority of others are also 10 degrees around 90 degree.

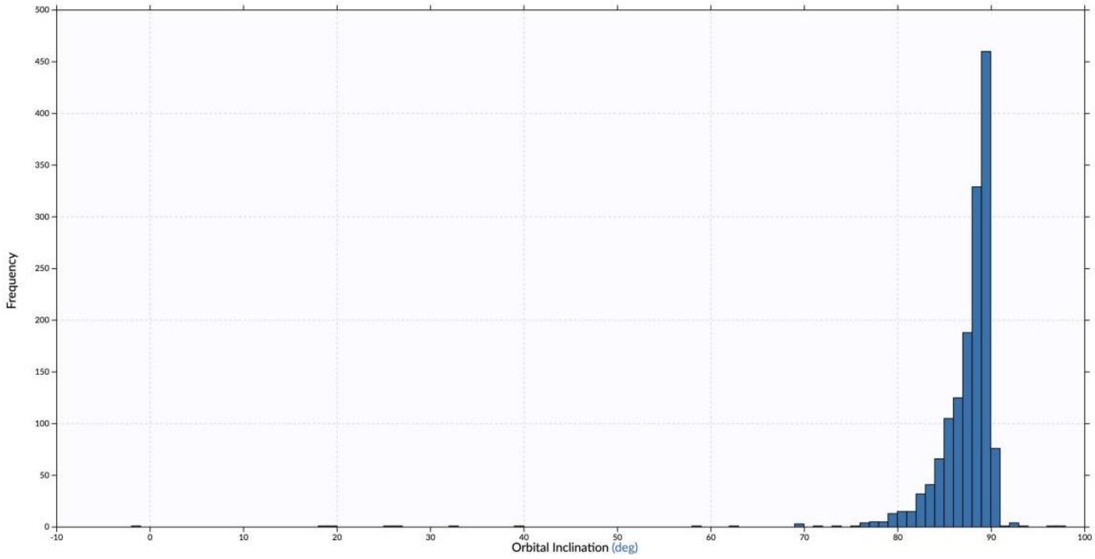

Fig. 1 Graph of i discovery by transit method.

The discovery of temperature of exoplanets by transit method is 1157, out of the total 1309, which is about a dominating 88.4% [14]. This could be explained by the fact that calculated temperatures of exoplanets are usually calculated from energy emission data, which is related to surface area, and thus the transit method may be useful in this perspective. Discovery of geometric albedo of exoplanets by transit method is 16, out of the 18 total, a dominating 8/9 [14]. The fact that there is a huge shortage in geometric albedo confirmation may be due to most exoplanets being too far away to measure this. Nevertheless, geometric albedo, or the reflection rate relative to a perfect smooth sphere, is one of major factors of secondary transitions' brightness data, so it is reasonable that most of the geometric albedo data confirmed are done by transit method. For the last property of focus, semi-major axis, 2317 discoveries were made by transit method, out of the total 3831 discoveries (percentage about 60.5%) [14]. Considering how frequently transit method is used, this is a moderate, or even minor amount. Similar to the usage of transit method on detecting orbital period, it is not significant enough to make a definite conclusion.

Overall, the frequency in using transit method to determine planetary radius, temperature, and geometric albedo is very high. While it is not so often used in determining planetary mass and orbital eccentricity. It is used moderately for detecting orbital period and semi-major axis, and it has an internal confirmation of orbital inclination. An example of a planet discovered by transit method is shown in Table 1, it shows the common features of exoplanets discovered by transit method [15]. From the table, it could be observed that the planetary radius is discovered by primary transit, and there is a calculated temperature, implying transit method's usefulness in determining these properties. The planetary mass was measured by radial velocity, which implies that RV method is better than transit method at this. There is no confirmed orbital eccentricity for this planet, since transit method cannot directly measure that. The geometric albedo is also missing, but given that there are only 18 exoplanets with confirmed geometric albedo, this is quite normal [14].

Table 1. TOI-3540 b.

Planetary mass	1.18 (± 0.14) MJ
Planetary radius	2.1 (-0.7 +0.0) RJ
Orbital period	3.119999 (± 8e-06) day
Orbital eccentricity	_
Orbital inclination	81.93 (-0.0 +1.2) degree
Calculated temperature	1498.0 (± 22.0) K
Geometric albedo	_
Semi-major axis	0.04289 (± 0.00093) AU
Mass detection method	Radial velocity
Radius detection method	Primary transit

3.2. Radial Velocity

The usage of radial velocity method over the years is also quite large, although not quite as staggering as the transit method. A total of 1104 exoplanets were confirmed by the RV method, which by division, is about 2/7 of the usage of transit method [13]. This might be an implication that from a holistic perspective, RV method is not as useful as transit method. However, for fairness, the data about RV method's usage would still be multiplied by 3.5, as to make a fair parallel comparison between the two methods. As with the analysis of transit method, the analysis of RV method would be made from its advantage/disadvantage in determining planetary mass and radius, orbital period, eccentricity and inclination, temperature, geometric albedo, and semi-major axis of exoplanets. RV method is especially useful in determining planetary mass. Out of the 3101 total discoveries of planetary mass, 1097 were made by RV method (percentage about 35.4%) [14]. If multiplied by 3.5, rises to 3839.5, which is far more than the 1374 made by transit method [14]. This may be because the observed redshift data of the Doppler effect could be directly used to determine its mass (the mass itself is inside the formula).

However, out of the 4029 planetary radius discoveries, only 77 were discovered by RV method (percentage about 1.9%) [14]. Even if multiplied by 3.5, the number 269.5 is still far less than the 3847 discoveries by transit method [14]. This may be due to the fact that planetary radius could only be related to the planet's Doppler effect by density (density and planetary radius effects mass, which is the result of radial velocity calculation). Since density is rarely able to be measured directly, RV method usually cannot be used to determine planetary radius. The orbital period discoveries by RV method is 1098, about 21.4% of the 5132 total discoveries [14]. Multiplied by 3.5, the number 3843 is very close to the 3884 discoveries by transit method [14]. This implies that they may be equally useful to be used for detecting orbital period. This may be related to the fact that orbital periods are not connected empirically to mass or surface area, so both methods achieve same usefulness in this perspective. The orbital eccentricity discoveries by RV method is 1048, roughly 44.7% of the total 2344 discoveries [14]. This is another property that RV method specializes on detecting, multiplied by 3.5, the number 3668 is over three times more than the 1201 discoveries by transit method [14]. This may be due to the effect that orbital eccentricity has a close relationship with the relative masses of the star and planet (the masses effects the center of gravity where they orbit each other on).

There are only 111discoveries of orbital inclination by RV method, just about 6.6% of the total 1678 discoveries [14]. Even multiplied by 3.5, the number 388.5 is far less than the 1502 discoveries by transit method [14]. One reason for this may be that the radial velocity data calculated by redshift could imply infinite different cases of orbital inclination. Besides, radial velocity didn't require any particular orbital inclination to be used for detection, so unlike transit method, the fact that it was done didn't imply anything about the orbital inclination. Only 88 calculated temperature discoveries were made by RV method, about 6.7% of the total 1309 discoveries [14]. After multiplied by 3.5, the number 308 is still less than a third of the 1157 discoveries made by transit method [14]. This may be due to the fact that the surface temperature of an exoplanet did not have any definite relationship with its mass (which is the main data gathered by RV method).

Two geometric albedo discoveries were made by RV method, a ninth of the total 18 discoveries (together with transit method, they made up every discovery of this) [14]. Multiplied by 3.5, the number 7 is less than the 16 discoveries by transit method [14]. This may be because the reflection rate of a planet does not have any kind of relationship with its velocity around its orbit. A total of 1039 semi-major axis were detected by RV method, a fraction of about 27.1% of the total 3831 discoveries [14]. If multiplied by 3.5, the number 3636.5 is larger than the 2317 discoveries by transit method [14]. The reason for this may be that the semi-major axis is related with the orbital eccentricity, which has a close relationship with the planetary mass, which RV method exceed at measuring. An example of a planet discovered by RV method is given in Table 2, it shows the common features of exoplanets discovered by RV method [16]. From the table, it could be observed that the planetary radius, orbital inclination, temperature, and albedo are missing, the "radius detection method" is also missing since the radius is not detected. These properties are considered the properties that RV method are usually not used for. However, the mass, eccentricity, and semi-major axis are present, with very little inaccuracies, which implies that RV method can detect these properties with accuracy (with enough technology to be precise enough). The orbital period is also present, which shows that RV method is able to detect this, in line with the analysis in prior parts.

Table 2. Gaia-3 b.

Planetary mass	0.79 (-0.04 +0.05) MJ
Planetary radius	_
Orbital period	310.9 day
Orbital eccentricity	0.948 (± 0.004)
Orbital inclination	_
Calculated temperature	_
Geometric albedo	_
Semi-major axis	0.799 AU
Mass detection method	Radial velocity
Radius detection method	_

4. Limitations & Future Outlooks

This study has a lot of limitations. Specifically, one huge problem for this research is that the author uses two parallel ways, one correlational and one purely theoretical but not empirical, to evaluate the detection methods. This could make the results very inaccurate, since the two approaches didn't actually link together using empirical tools. Another limitation with this research is over the properties that the researcher considers "major". What properties are to be considered major were determined by the researcher's own understanding of the public consensus, and that could be very subjective and effect the findings. Another problem about subjectivity is over the "representative" planet in the results section, the planets may be chosen out of some subjective criteria, and effecting the validity of the example. One more major limitation presented in this paper is the choose of source (database). Although an authority website, exoplanet.eu, was chosen as the database of sources, there could still be some inaccuracies, since the source is just too single to avoid random errors completely.

One other limitation lies with the status of the planets. Every planets involved in this paper are noted as “confirmed”. This paper did not, therefore, show consideration for the candidates and unconfirmed exoplanets. Moreover, the data evaluated about the usage of each exoplanet detection method is gotten directly from the “plot” section of exoplanet.eu, which, although uses data directly from the “catalog” section, may ignore some details (for example, a lot of planets’ properties were gotten from multiple different detection methods, but the plotting section may make some errors about this fact).

For future researches, the above issues could be addressed and improved upon, and even more could be done. With more mathematical knowledge, future researches could use a more empirical method to do similar researches. The problem about subjectivity could be reduced by expanding the properties and exoplanet sample to be analyzed, both to reduce subjective flaws over which properties are major and which planets are representative, and to broaden the findings. For the source of information, the database could also be expanded. Sources like NASA’s official websites and some government certified astronomy archives could be used together with exoplanet.eu. One more improvement could be done upon the status of the planets, in which consideration and analysis of candidates and unconfirmed exoplanets could be shown. The data about usage of detection methods on different exoplanet properties could also be improved, one plausible way is to use some kind of tool that could analyse the data from “catalog” section of exoplanet.eu or other verified sources directly into the wanted information, instead of using something like the “plots” section as an intermediate. Beyond these improvements, future researches could actually improve and expand upon the subject itself, such as bringing in evaluation of different types of telescopes in respect to different methods of exoplanet detection, a detailed graphic analysis of different detection methods on different properties (this paper did not include graphic analysis), and the various types of exoplanets that each type of telescopes could observe (and possibly conclude a limitation and improvement upon telescope technology).

5. Conclusion

To sum up, this study investigates into the transit method and radial velocity method of exoplanet detection. Based on the anaysis, transit method exceeds in determining planetary radius, temperature, and geometric albedo, while RV method are not useful to determine these properties. RV method is very useful in determining planetary mass and orbital eccentricity, yet transit method is not as useful for these properties. The two methods are both moderate in detecting orbital period and semi-major axis (RV method is slightly more useful in determining semi-major axis). Besides the internal confirmation of transit method’s near 90 degree, both methods are not so useful at determining inclination (which meant that: 4b.Both methods are not very useful at detecting orbital inclination at angles far from 90 degrees). Geometric albedo are rarely confirmed, so whether which method, limited detection were made. Nevertheless, the research has a lot of limitations like subjectivity, source of information, and lack of empirical methodology. Future studies could address upon these issues, and do even more on the subject of exoplanet searching, such as bringing in the topic of different types of telescopes and telescope technologies. This paper did an analysis on the relative advantages and disadvantages of transit method and radial velocity method, providing insight into which detection method to utilize/search for when trying to find specific data about certain properties. It might be useful as an amateur guide to fellow students on exoplanet detection methods.

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