The Comparison of Five Methods of Detecting Exoplanets

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Abstract. Detecting exoplanets has become a hot topic, where various detection scenarios have been proposed. Five of these methods have all found more than 50 exoplanets, which are the transit method, the radial velocity method, the microlensing method, the imaging method, and the timing method. This paper aims to find their pros and cons, and the type of exoplanet that is suitable for each method by comparing the characteristics of exoplanets found by each method and the detection result of each method. The transit method is suitable for exoplanets with short periods possessing the advantages of measuring various parameters of exoplanets simultaneously, but can confuse exoplanets and other celestial bodies with the same radius of planets. The radial velocity method is best for exoplanets with small orbit radius or large mass, whereas it can only determine the minimum mass of exoplanets. The microlensing method can find exoplanets that are extremely far from the Earth or even rogue planets, as well as their mass. However, it does not allow researchers to observe the exoplanets found by it twice. The imaging method offers a tool to directly observe exoplanets in the infrared band. It can detect exoplanets that are extremely far from their host star with relatively high temperatures or rogue planets, but these are also the types of exoplanets that it can be detected. The timing method allows observers to discover exoplanets around pulsars, pulsating stars, eclipsing binaries, and planetary systems with discovered planets, but it is limited to these types.

Keywords: exoplanet; comparison; detection method.

1. Introduction

Researchers have wondered about the existence of planets out of the solar system for centuries. Until 1992, the first exoplanet has been found around a pulsar, PSR 1257+12 [1]. Afterward, more and more exoplanets have been found with a higher and higher frequency. Until August 2022, people have already discovered more than 5000 confirmed exoplanets [2]. The reason why researchers are so interested in looking for exoplanets is that they are extremely meaningful to humans. Based on investigations of young planetary systems which contain exoplanets or dust disc, scholars can know the way the Earth and the solar system is formed. Research on older planetary systems will also tell people what will happen to the Earth billion years later. In addition, scholars are looking for planets that are available for life to live on it. Intelligent life may be found on this basis. To achieve these goals, plenty of different methods are proposed to search for exoplanets.

The majority of the exoplanets were found by the transit method, which detects exoplanets by looking for the occurrence of transit. The first exoplanet found by transit is OGLE-TR-56b, which is found in 2002 [3]. Subsequently, more and more exoplanets are discovered by this method at an increasing speed. Until August 2022, more than 3800 exoplanets have been found by this method [2]. The radial velocity method is a method that looks for exoplanets by checking the shift of the spectrum nets [2]. When the Earth, an exoplanet, and a star (not the host star of the exoplanet) are in a straight line, the brightness of the star will dramatically increase due to the gravitational microlensing effect caused by the gravity of the planet. By this principle, OGLE-2003-BLG-235Lb was discovered in 2004, as the first exoplanet discovered by the microlensing method [5]. Until August 2022, more than 130 exoplanets have been found by this method [2]. Imaging is a method that looks for exoplanets by looking for the infrared radiation emitted by the exoplanet. The first exoplanet that has been discovered by the imaging method is 2M1207b, which is discovered in 2004 [6]. More than 60 exoplanets have been found by this method up to August 2022 [2]. The gravity of exoplanets will affect the period of some special stars like pulsars in observers' eyes by causing motions of the star or affecting the period of the occurrences of transit of another planet in the same planetary system.

The method of looking for exoplanets by observing these phenomena is called the timing method. The first exoplanet has been discovered is found by this method around a pulsar in 1992 [1]. 50 exoplanets have been found by this method until August 2022 [2].

To compare the five approaches for planet searching, this paper illustrates the different cases for better understanding. In the following, this paper will introduce the principle of each method with some formulas, the research result got by each method, and compare the pros and cons of these methods by the compare the characteristics of the exoplanets that have been discovered by different methods. These five detecting methods are the methods that discovered most of the exoplanets, while they are not all the methods people have invented. The reason other methods are not chosen is that there are only fewer exoplanets found them.

2. Descriptions & Principles of different methods.

2.1. Transit

Transit is an astronomical phenomenon, which happens when the Earth, an exoplanet, and its host star are in a straight line so that the planet will block a part of the light of its host star. As the result, the observer on Earth will notice that the brightness of the star dropped, as shown in Fig. 1 [7]. By observing the transit of an exoplanet, scholars can get the following data: P (period of transit), ΔF (change of the host star's brightness, in percentage, t_T (time duration of transit), t_F (duration of the lowest brightness state). Based on these data, the radius of the planet, R_p, orbit semi-major axis, a, radius of the host star, R_*, mass of the host star, M_*, eccentricity, e, and inclination angle, i, can be found. For example, based on the data, R_p, the radius of the planet can be calculated if R_* the radius of the host star is known [7]:

$$\Delta F = \left(\frac{R_p}{R_*}\right)^2 \tag{1}$$

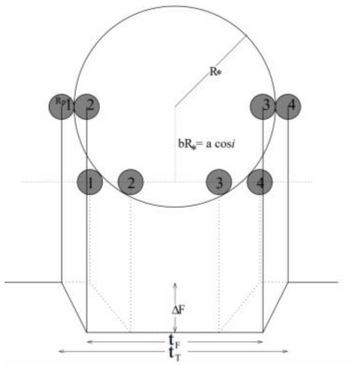

Fig. 1 The light curve and position of the exoplanet relative to its host star.

2.2. Radial Velocity

If a star has a planet or planets, then the star-planet system will rotate around the center of mass of the whole system. This will make the star move in a circular or elliptic orbit. To the observer on the Earth, the star has a periodically changing line-of-sight velocity. This leads to periodic red and blue shifts of the spectrum of the star, which can be captured by the telescope on Earth. By measuring the degree of shifting in a specific wavelength, Δλ, and its original wavelength, λ the line-of-sight velocity of the star, v can be calculated through the following formula,

$$\frac{\Delta\lambda}{\lambda} = \frac{v}{c} \tag{2}$$

Where c represents the velocity of light. By plotting a Velocity-Time graph, the maximum velocity of the star, K, and the period of the star's motion, T, can be determined. For example, as shown in

Fig. 2, the 18 Delphini has a maximum radial velocity of 119 m/s and a period of movement of 993 days [8].

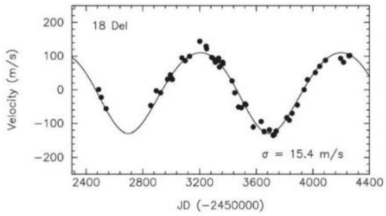

Fig. 2 Radical velocity of 18 Delphini as a function of Time.

Then, the minimum mass of the planet, $M_p sini$, can be calculated

$$K = \left(\frac{2G\pi}{T}\right)^{\frac{1}{3}} \frac{M_p sini}{\left(M_p + M_*\right)^{\frac{2}{3}}} \frac{1}{\sqrt{1-e^2}} \quad (3)$$

Where G represent the universal gravitational constant, M_p represents the actual mass of the planet, i represents the orbital inclination (angle between observers' sight and the axis of revolution of the exoplanet), M_* represents the mass of the host star, and e represents the eccentricity of the exoplanet's orbit. By identifying i through the transit method, the actual mass of the exoplanet can also be calculated.

2.3. Microlensing

The gravity of a star can bend light. When two stars and the earth are in a straight line, the star between the earth and another star bends the light emitted by the star at back, hence the star between the earth and another star works like a convex lens, which focuses the light from the star at back on earth. Thus, the brightness of the star at back will dramatically increase as illustrated in the left panel of Fig. 3 [9]. However, when the star has a planet, the gravity of the planet will also cause a microlensing event while the microlensing event caused by the host star is happening as presented in the right panel of Fig. 3 [10]. By this method, the mass of the exoplanet can be determined.

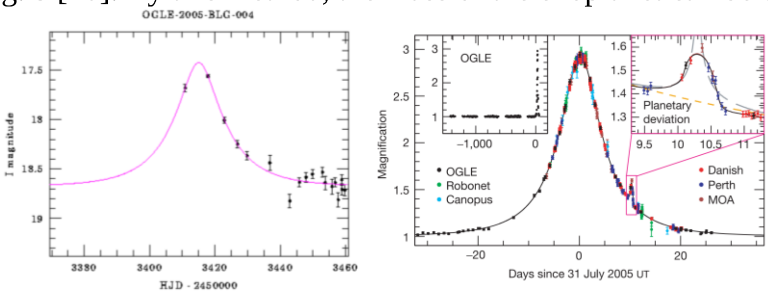

Fig. 3 The light curve of OGLE-2005-BLG-004 (left panel) and the light curve of the OGLE-2005-BLG-390 microlensing event (right panel). For the latter one, it is caused by OGLE-2005-BLG-390Lb and its host star, the smaller crest is caused by OGLE-2005-BLG-390Lb.

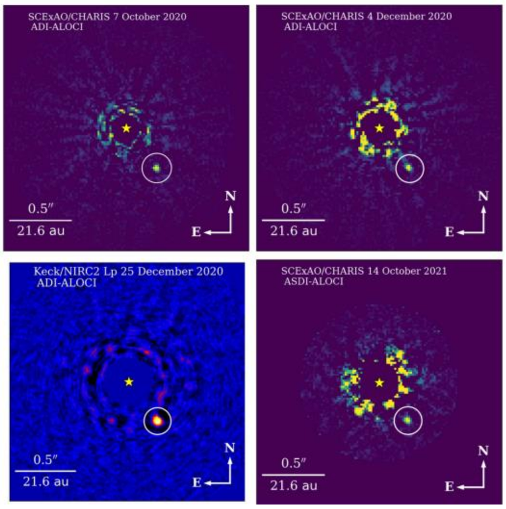

Fig. 4 Images of HIP 2112B.

2.4. Imaging

Imaging is a method that allows scholars to directly "see" the exoplanet in the infrared spectrum. Exoplanets reflect visible light emitted by their host stars; but the brightness of exoplanets is extremely low compared to their host star, which makes the exoplanet invisible. In the infrared band, exoplanets emit radiation due to their own heat. Though their brightness is still very low compared to their host stars, exoplanets are already visible in this wave band. By blocking the radiation emitted by the host star with a coronagraph, the infrared radiation emitted by the exoplanet can be detected. Besides, the exact orbit of the exoplanet can be determined by observation and the temperature of exoplanets can be determined by the inferred radiation emitted by the exoplanets [11]. An example of the images of HIP 2112B is presented in Fig. 4.

2.5. Timing

If a star has a planet or planets, then the radial distance between the star and the earth changes periodically due to the same reason mentioned for the radial velocity method. Therefore, the time for light travels from the star to the Earth also changes. Consequently, if the host star has a stable period, for example, the host star is a pulsar, then the length of its period will change periodically. Due to the change of the radial distance between the pulsar and the Earth, each pulse will arrive earlier or later than the predicted arriving moment (in the absence of the planet), since the change of distance leads to the change of time for each pulse takes to travel. The amplitude of variation in time of arrival, τ_p, can be determined, as depicted in Fig. 5. Subsequently, the minimum mass of the planet, $M_p$sini can be calculated as

$$\tau_p = \frac{1}{c}\frac{a\sin(i)\,M_p}{M_*} \quad (4)$$

Here, c represents the velocity of light, M_p represents the actual mass of the planet, i represents the orbital inclination, M_* represents the mass of the host star, and a represents the semi-major axis of the exoplanet's orbit [12].

Except for pulsars, there are many other celestial bodies has their own periods, such as pulsating variable stars and eclipsing binaries. Exoplanets orbiting them can also be detected by the same principle of pulsar timing. In addition, if a planetary system has more than one planet, then the gravity between the planets will accelerate or decelerate each other. For the planetary system with one planet, the period of transit of a planet is a constant number. However, in a planetary system with multiple planets, the velocity of each planet keeps changing due to the gravity of other planets. Thereby, the period of transit of one planet won't be a constant. When observers found the change in the period of transit of a discovered exoplanet, then observers can predict that other planets exist in this system. It is known as TTV (transit timing variation), which can determine the maximum mass of the potential exoplanet.

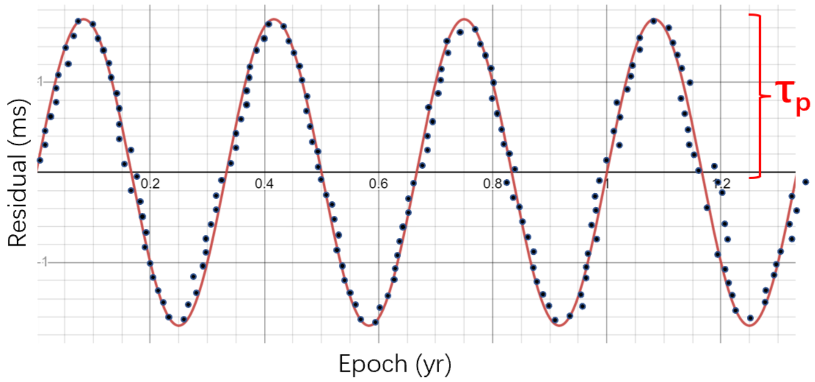

Fig. 5 This is a schematic diagram of how τ_p is found. Each black dot represents a pulse emitted by the pulsar. The y-axis shows the residual between the actual moment for each pulse arriving at the Earth, and the predicted value of arriving moment if the pulsar has no planet. The red curve is the sine curve that fits these dots.

3. Detection results

3.1. Transit

Since 2011, the transit method has become the main method researchers used to discover exoplanets [13]. Over the 3879 exoplanets discovered by the transit method, more than 3500 of them have an orbital period of less than one year [2, 13]. Notably, the majority of planets found by transit are found by the Kepler telescope, which is launched in 2009, and continuously work until 2018 [2]. As shown in Fig. 6, the biggest green area made by dense green dots at Ra-300, Dec-50 is the area where the Kepler telescope looked for exoplanets while it took the Kepler mission from 2009 to 2013, which each green dot represents an exoplanet found by the transit method. Kepler telescope found more than 2700 confirmed exoplanets in this area [2, 14]. From 2013 to 2018, the Kepler telescope stopped the Kepler mission and started the K2 mission. As seen in Fig. 6, there is a green curve made by several green spots around the Dec-0 line. Most of the exoplanets in these green spots are found by the Kepler telescope during the K2 mission, in which is a total of 537 confirmed exoplanets found during the K2 mission [2, 14]. Then, the TESS telescope was launched to carry on looking for exoplanets by transit. By August 2022, it has found more than 230 confirmed exoplanets [2].

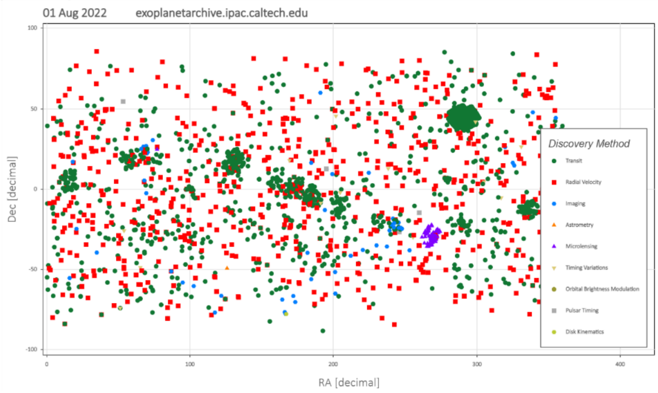

Fig. 6 Exoplanets found by different methods on a sky map.

3.2. Radial Velocity

Until 2010, the radial velocity method was the most important method of detecting exoplanets [13]. By August 2022, 936 exoplanets have been found by the radial velocity method [2]. As shown in Fig.

7, exoplanets found by the radial velocity method can be divided into two groups, either having a mass greater than Jupiter or having a small orbit radius, around 0.1 au [14].

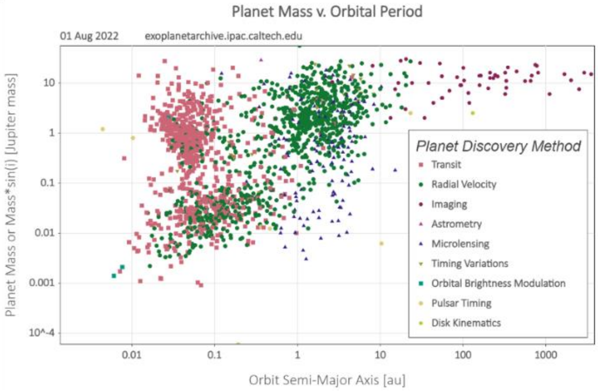

Fig. 7 The mass and Orbit Semi-Major Axis of exoplanets found by different methods.

3.3. Microlensing

Up to August 2022, 132 exoplanets have been found by the microlensing method [2]. Most of them are found by the OGLE (Optical Gravitational Lensing Experiment), the MOA (Microlensing Observations in Astrophysics), and the KMTN (Korean Microlensing Telescope Net) at the galactic center direction, as shown in Fig. 6, a purple area made by small purple triangles, each purple triangles symbolize an exoplanet found by the microlensing method. Importantly, most exoplanets found by this method have an orbit semi-major axis between 1 au to 10 au, and are extremely far away from the earth, most of them are between 4000 pc to 8000 pc away from the earth, shown in Fig. 8. On 2020, the first rogue planet, OGLE-2016-BLG-1928, was found by this method [15].

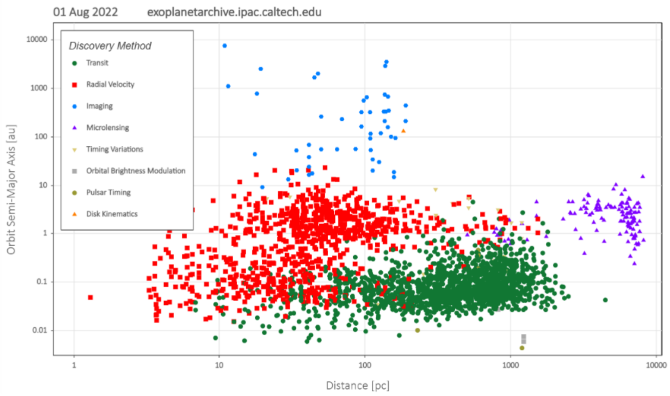

Fig. 8 Orbit Semi-Major Axis and Distance from the Earth of exoplanets found by different methods [14].

3.4. Imaging

By August 2022, there are 61 exoplanets found by the imaging method. Compare with exoplanets found by other methods, they are extremely far from their host star. As presented in Fig. 9, the farthest one, COCONUTS-2 Ab is 7506 au away from its host star. However, the inversed relation between the orbit radius and temperature of exoplanets does not apply to planets discovered by imaging. Most of the equilibrium temperatures of exoplanets found by imaging are between 1000K and 3000K, which is a relatively high temperature [14].

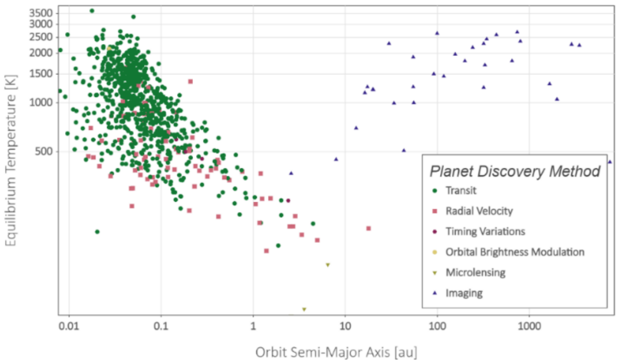

Fig. 9 The Orbit Semi-Major Axis and the Equilibrium Temperature of exoplanets found by different methods.

3.5. Timing

The timing method can be used as long as the host star or even the planetary system of the exoplanet has a period, therefore, there are different kinds of timing methods. Until August 2022, 7 exoplanets are found by pulsar timing variation (timing by pulsar), 2 planets are found by pulsating time variations (timing by pulsating stars), 18 exoplanets were found by eclipsing timing variations (timing by eclipsing binaries), and 23 exoplanets found by TTV (transit timing variation) [2]. Fig. 10 shows the change in the period of a pulsar, PSR 1257+12, due to the gravity of its two planets. Due to the change of the radial distance between the PSR 1257+12, the change of arriving time of each pulse also changes periodically, as exhibited in Fig. 11, which is an example of discovering exoplanets based on the timing method [1].

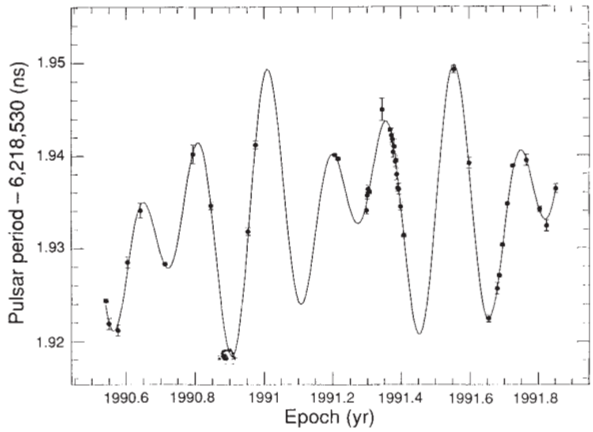

Fig. 10 Period variations of PSR 1257+12.

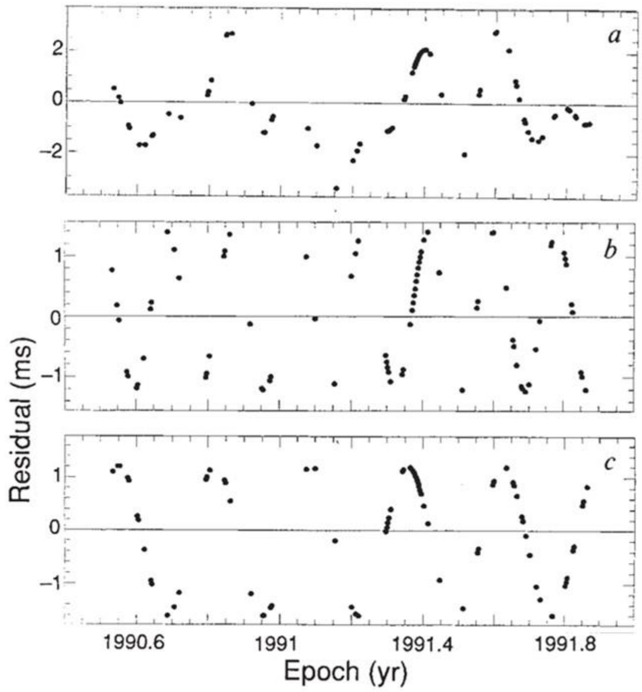

Fig. 11 the first graph shows the deviation of the arrival time for each pulse (arrive earlier or later than the average value), the first graph is the combination of the second graph and the third graph, which indicates the separated effect of the two planets on the deviation of the arriving time for each pulse of the PSR 1257+12.

4. Comparison

By comparing the detection results of different methods, the type of exoplanets that are suitable for each method and the pros and cons of each method can be found.

4.1. Transit

Most of the exoplanets found by the transit method have relatively short periods as illustrated above, this indicates that transit is especially good at finding exoplanets that are closer to their host star, which matches Fig. 7, since the shorter the radius, the shorter the period. This is because observing and tracking transits of exoplanets with shorter periods is much easier than transits of exoplanets with long periods. The transit method allows researchers to acquire many parameters about the exoplanets found by this method, including radius, orbit radius, the radius of the host star, the mass of the host stars, eccentricity, and inclination angle. In addition, as the Kepler telescope and the TESS did, the transit method allows people to find thousands of exoplanets within a small area of the sky by just keep observing the brightness of stars in the area, i.e., it found the most exoplanets currently. However, the transit method cannot recognize if the transit is caused by exoplanets or celestial bodies that have the same radius as big planets, such as a brown dwarf. As the name of this method points out, this method only applies to exoplanets whose transit can be observed from the viewpoint of the Earth.

4.2. Radial velocity

The radial velocity method is suitable for exoplanets that have either a small orbit radius or a large mass. In other words, these are exoplanets that can cause greater impacts on the motion of the host stars and the shift of the spectrum of the host stars. Hence, it is easier for observers to detect the changes in the spectrum. Since the gravity of the exoplanet is directly proportional to the mass of the exoplanet and inversely proportional to the square of the distance between the exoplanet and its host star. It can only help researchers to identify the minimum mass of exoplanets, $M_p sini$. Fortunately, if the exoplanet can also be detected through the transit method, then by substituting i into $M_p sini$, the actual mass of the exoplanet, M_p, can be calculated.

4.3. Microlensing

The microlensing method can help researchers find exoplanets that are extremely far away from the Earth. In addition, similar to the transit method, by keep monitor the brightness of the star of a region in the sky, this method can help people find a large number of exoplanets, which is what OGLE and MOA doing currently. Microlensing can help researchers to determine the mass of exoplanets. Microlensing can also detect rogue planets. Whereas, the microlensing method fully relies on the occurrence of the microlensing event. It is almost impossible for researchers to detect the exoplanet found by the microlensing method twice since the microlensing event will not occur twice on the same exoplanet.

4.4. Imaging

The imaging method is especially good for planets that are extremely far away from their host star. Which is very difficult for the transit method and the radial velocity method to discover. Unlike the other four methods, which look for exoplanets indirectly, the imaging method allows researchers directly “see” exoplanets in the infrared band. Similar to the microlensing method, the imaging method can also be used to discover rogue planets. However, it is very difficult for the imaging method to find exoplanets that are not far away from their host star or colder (which only emits weaker infrared radiation).

4.5. Timing

If a star is a pulsar, pulsating star, or eclipsing binary, then the transit method cannot be used for looking for its planet since it has a changing brightness. Moreover, the radial velocity method cannot be used since these types of stars has relatively special spectrums. Therefore, timing is the best way to detect exoplanets orbiting around these types of stars. The TTV method can help researchers determine if there are other planets in the planetary system which has a planet that has been found and its transit can be observed from the Earth. However, the cons of the timing method are very obvious, it only applies to exoplanets either orbiting around special stars, including pulsars, pulsating stars, and eclipsing binaries, or in planetary systems that contain at least one discovered planet which can be observed in its transit from the Earth.

5. Limitation & Prospect

The data used in this paper, e.g., the number of exoplanets found by each method, is mostly coming from the database, NASA EXOPLANET ARCHIVE, that is updated on August 16th, 2022. However, exoplanet discovery developed rapidly recently, the number may have changed after this paper is published. There are also other methods of detecting exoplanets that have not been included in this paper due to the lack of data, e.g., the astronomy method and the disk kinematics method, which both only found one exoplanet [2]. In the future, more approaches can be compared and analyzed with more abundant data.

6. Conclusion

In conclusion, this paper compares five methods of detecting exoplanets based on their detecting results and the parameters of the exoplanets found by each method. Specifically, the transit method is good at detecting exoplanets with small orbit semi-major axis and is able to determine many parameters of exoplanets and find a large number of exoplanets by scanning a small area in the sky, whereas cannot recognize brown dwarf and exoplanets around a star. According to the analysis, the radial velocity method is suitable for exoplanets with small orbit semi-major axis or great mass. However, the minimum mass of the exoplanet is the only parameter it can find without the transit method. Besides, the microlensing method can discover exoplanets that are extremely far from the Earth or even rogue planets. It can also discover plenty of exoplanets by scanning a small area in the sky and finding their masses. Whereas researchers cannot keep observing exoplanets found by this method after the microlensing event. Moreover, the imaging method is the only way to detect exoplanets that are extremely far from their host star, it can also detect rogue planets, but it is helpless for exoplanets that are close to their host star. Last but not the least, the timing method provides a way to detect exoplanets that orbit around host stars (e.g., pulsar, or exoplanets) that have stable periods in planetary systems that contain other discovered exoplanets whose transit can be viewed from the Earth. However, it cannot be used to find exoplanets in a planetary system with one planet and a star without an obvious period. Nevertheless, the data used in this paper might be changed quickly. In the future, other methods can be added to this study after they find enough exoplanets and obtain enough data. Overall, these results offer a guideline for the exoplanar detection of exoplanets.

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