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# Transit and radial velocity method for exoplanet detection

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**Abstract.** This article introduces some basic methods that human usually uses nowadays to detect exoplanets, including transits method, radial velocity method, direct imaging method, gravitational microlensing method, and astrometry method. As we all know, none of these methods are perfect, each of them has its advantages: some of them are good at detecting planets with great mass, some are good at detecting planets with great radius, and some of the methods are good at detecting planets far away from their host star. But at the same time, each method has its own disadvantages. That is the reason why sometimes some of these methods are used together to get information about specific exoplanets. This chapter will introduce these methods by giving information on how these methods work, the equipment each of them requires, the advantages and limitations of these methods, and the history and development of these methods. Finally, there is a conclusion that states the characteristics of the planets each method is good at detecting.

**Keywords:** transit, radial velocity, gravitational microlensing, astrometry, exoplanet detection, history.

## 1. Introduction

As the technology develops, human beings are learning more and more about the universe we are in. However, the more we learn about the universe, the more mysteries appear in our sight. Scientist are working hard to solve these mysteries. At the same time, apart from revealing the truth of the universe, the scientists are also using the knowledge of the universe to help the development of human civilization. One of the greatest uses of is to find a second home for human beings. As human civilization develops, the population grows rapidly. However, the total amount of resource on the Earth is constant, and one day will be used up. Pollution is also an important factor. The environment of the Earth is being polluted and one day it might be no longer suitable for human beings to live in. Considering these two reasons, astronomers are working hard to find another planet that are suitable for human to live in. Over the past 500 years, scientist have developed several methods to detect exoplanets, and we are going to talk about some of them in the following passage.

[1-9] talks briefly about the exoplanet detection methods we often use nowadays, including the information of how these methods work, calculations included in these methods, and so on. For transit method, [10] explained it in detail; [11] talked about the advantage of transmit method, which is it gives information about composition of the planets' atmosphere; [12] introduces detailed calculations of the mass and orbit that can be deducted by observing transiting planets. [13, 14] go deep in radial velocity methods and provides a great amount of information to the readers. [15-17] are about direct imaging

methods. They introduced it in aspect of principal, calculations, multi-colour photometry, and so on. [18] talks about detection of exoplanets using combination of radial velocity method and direct imaging method. [19] and [20] talk about gravitational microlensing and astrometry as methods for exoplanet detection. And finally, as a summarization, [21] discusses about and compares between methods that include direct observation of the planets and methods that do not.

## 2. Notations

For simplicity's sake, the chapter will use * and p as notation for stars and planets. Therefore, we will have $M_*$ and $M_p$ for the mass of the star and the planet, $R_*$ and $R_p$ for the radius of the star and the planet. Furthermore, for simplicity, this article will not include any calculation related to the angle of incidence and so on.

## 3. Principle of methods

In this section, we introduce the principle of method used in this paper. They are respectively illustrated in Subsections 3.1-3.5.

### *3.1. Transit method*

The transit method is a method of detecting exoplanets by observing transits of the planets. Transits are when exoplanets travel between its host star and the Earth. When the planets are transiting, some of the light emitted by the host star will be blocked by the planet. Thus, the intensity of the star we observe will decrease during transits. By measuring the flux, or in another word, the change in intensity, we can calculate the radius of the planet using the formula $\Delta I = \frac{L}{4\pi {R_p}^2}$. Also, by measuring the time gap between two transits, we can get information for the period T that the planet orbit around its host star.

### *3.2. Radial velocity method*

Radial velocity is an indirect method of detecting exoplanets. The reason why it is indirect is that the existence and the information of the exoplanets it detects are not directly observed, instead, they are deducted. In another word, people do not have to observe the planet directly to detect it. As we all know, the center of mass of a star is at its center. However, if a planet exists in the stellar system, the center of mass of the entire stellar system will be shifted. Even though in a small scale, this shift of center of mass of the stellar system will cause the star to orbit around the center of mass. According to the theory of Doppler effect, which is the frequency and wavelength of the light the star emit will change as the star moves. When the star is moving toward us the frequency of the light we observe will be $f = \frac{f_0}{v - v_*}$, which is blueshift. On the other hand, when the star is moving away from us the frequency observed will be $f = \frac{f_0}{v + v_*}$, which is redshift. As the star orbits around the center of mass, it will blueshift and redshift periodically. With this detection method, we can deduce the orbital period, the orbital radius, the mass of the planet and so on. The orbital period of the planet is exactly the same as the orbital period of its star around the center of mass. The mass and its distance from its star determine how much the center of mass of the whole system is shifted from the center of mass of its host star. The further and greater mass the planet has, the more the center of mass of the system will shift.

### *3.3. Direct imaging method*

As it is called, direct imaging is a very simple method and is very easy to understand. Direct imaging method detects exoplanets by simply taking photos of the stellar system and identify planets from the photos taken. As everyone knows, planet will receive light from its host star and at the same time reflect it to other directions. Some of these reflected lights will travel in the space and reach the Earth, and thus become detectable. Using this method, scientists can detect exoplanet in almost every orbit and can get direct information of the temperature, composition, atmosphere, and so on about the planet.

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### *3.4. Gravitational microlensing method*

Gravity is the force by which a planet or other body draws objects towards its center. As we all know, gravity plays an important role in astronomy field. It causes celestial bodies attract each other and is the key for planets to orbit around their host stars. However, gravity even has an effect on lights traveling in the space. Even in a small scale, the effect of gravity on light can give us critical information when detecting exoplanets. Usually, the light of the distant star travels in a straight line through the space and finally reach the Earth for us to observe. However, when there is a planet between the Earth and distant stars, the light those distant stars emit will be bent by the planet and travels in a curved line. The small effect of gravity on the light will be enlarged by the enormous distance between the Earth and the planet. If we are able to detect the change in track of light emitted by the distant stars, we can successfully deduct the existence of an exoplanet between the distant stars and the Earth. And with the information we get, we can calculate the mass of the planet and its distance to its host star.

### *3.5. Astrometry method*

Astrometry is a term in astronomy which deals with precise measurements of the positions and movements of celestial bodies. It had been used by human beings for thousands of years and played an important role in human beings' recognition of the universe we are in. By using telescopes, scientists are able to observe and measure the relative position of the star comparing to the stars around them. By observing and recording the position of the stars in the sky for a period of time, we can draw a track of how the stars are moving in the sky. Usually, the track of the stars should be a straight line or a smooth curve. However, if a planet exists in the stellar system, like what has been stated in the radial velocity part, the center of mass of the whole stellar system will shift away from the center of mass of the star. In this case, the star itself will orbit around the center of mass of its system and form a spiral or circular trial according to different angle we are observing. Thus, if the trail of the star we observe is spiral or circular, we can know the existence of planets in its system and deduct information like the mass of the planet, orbital period, distance to the host star, and so on.

## 4. Advantages and limitations

### *4.1. Transit method*

Transit method, as one of the most commonly used method at detecting exoplanets, has plenty of advantages. For example, it is easy to use, only requiring a camera and a telescope, and it provides the scientist various of information, such as distance from the star, size, density, composition of atmosphere, and so on. However, there are also limitations. It might take a long period of time to observe a second transit of a planet, objects like sunspots might be recognized as transiting planets, and most importantly, transit method can only detect planets that exactly travel between its host star and the Earth, which is not a large fraction.

### *4.2. Radial velocity method*

Radial velocity method detects exoplanets mostly by deductions and calculations, thus have advantages on detecting relatively smaller planets, also, it provides critical information of the planets' masses, which is rarely provided by other detection methods. These are two main advantages of detecting exoplanets using radial velocity method. Meanwhile, the limitations of this detection method are very obvious. It requires accurate devices to measure blueshifts and redshifts, it can only detect planets close to its host star as only such planets can cause the shift in center of mass of the system large enough for detection, it will not be efficient when the plane where the orbit of the planet is on is perpendicular to our sight, and it gets complicated and difficult to calculate when detecting complex stellar systems, such as binary systems or systems containing multiple planets.

### 4.3. Direct imaging method

Direct imaging method is a method which provide plenty of useful information, such as the atmosphere, temperature, and compositions. Also, it requires nothing but a astronomical telescope, which is also one of the greatest advantage of using direct imaging as detection method. However, limitations of this method are also direct. When scientists are trying to detect exoplanet using direct imaging method, they have to align the telescope with the direction of the star. Thus, a special light filter is required because the light reflected by the planets are so dim comparing to the light emitted by the star itself. In this case, the filter needs to be very accurate so that it will block the light emitted by the star, while not blocking the light reflected by the planet. Due to this reason, the direct imaging method is considered to be better at detecting planets further away from its star than those which are close. Furthermore, as the amount of light reflected is determined by the surface area of the planet, the method is less efficient at detecting relatively smaller planets.

### 4.4. Gravitational microlensing method

Finally, gravitational microlensing method also has its advantages and disadvantages. The method is especially good at detecting planets in the outside stellar system. This is because the information it requires, the gravitational effect on the lights passing near the edge of the planet, is relatively independent from the planet's host star. However, this advantage also leads to a critical limitation of the method. This method does not depend on information from its host star, but it might be affected by the host star. As we all know, the star usually has much greater mass than the planets orbiting around them, and thus has much greater effect on distant lights and greater gravitational microlensing than the planets do. Because of this, the method is much less efficient at detecting planets closer to its host star. Also, to identify difference in distant light in a small scale, a precise, alignment between the planet, its host star, and the Earth, which does not happen very often.

### 4.5. Astrometry method

Detecting exoplanets using astrometry method requires extremely precise equipment, including telescopes with high-resolution camera and precise tracking system, and atomic clocks to synchronize observations from different telescopes and to measure the precise time taken for the measurement. Comparing with other methods of detecting exoplanets, astrometry is able to provide extremely precise data on the position and motion of the planet. However, apart from the advantage, limitations appear as the demand for high precision measurement of the data. Stars are very far away from us, so the angular speed ω, which equals to $\frac{v}{r}$, of the distant star we observe will be extremely slow, so precise data is required to deduce the existence and information about the planet. However, the thickness of the Earth's atmosphere is not the same everywhere, some region the air is denser, while other regions the atmosphere is not so dense. This would cause different rate of refraction and prevent scientists from getting precise data. Thus, it is hard for people to get precise information on the ground, which is later solved by sending telescopes into the space.

## 5. History and development of the detection methods

### 5.1. Transit method

The time when human first recognize the period-luminosity relationship is in the late 19th century. However, transit method is not widely used until the Kepler spacecraft is launched into the space in 2009. With the help of the spacecraft, transit method had become one of the most commonly used methods to detect exoplanets.

### 5.2. Radial velocity method

The idea of detecting exoplanets using radial velocities of their host star was first proposed by astronomer Otto Struve in 1950s, but the time when the method was used widely was only after the development of high-precision spectroscopy. With the help of radial velocity method, plenty of exoplanets including hot Jupiter, super-Earth, and so on.

### *5.3. Direct imaging method*

The concept of direct imaging method in the field of exoplanet detection first appeared in 1970s, but it is restricted in a short range of astronomers due to its high production cost. As the technology developed, people are able to produce more advanced optics systems and coronagraphs with much cheaper price than before, and in the 2000s, direct imaging method became a practical method for detection of exoplanets.

### *5.4. Gravitational microlensing method*

The gravitational microlensing method first appear in astronomers' sights in the 1980s. In fact, the gravitational microlensing method would not be an efficient method for exoplanet detection if an advanced database was not presented. So actually, it is after 2000s, when the large-scale survey and data analysis techniques were developed and advanced, that the gravitational microlensing method became a practical method for exoplanet detection.

### *5.5. Astrometry method*

In the 19th century, the astronomer Friedrich Bessel had made great contributions on the development of the astrometry method. He created precise equipment to measure the stars' positions and to calculate their distances to the nearby stars. This has laid foundation for the coming generations to further develop astrometry method. Finally, in the early 20th century, the timing method was improved and astrometry method finally become a successful method of detecting exoplanets.

## 6. Conclusion

Each method for detecting exoplanets has its own advantages and disadvantages. The transit method is useful when detecting planets that are passing directly in front of their host star, and provides rich information about the planet's size and distance from the host star. The radial velocity method is good at detecting smaller planets that are closer to their host star than the transit method and provides information about the planet's mass. The direct imaging method is useful as it detects the planet directly and provides detailed information about the composition and atmosphere of the planet, but it is comparatively more difficult and expensive to use. The gravitational microlensing method is useful for detecting planets in the outer regions of a star system, but it requires a specific alignment between the planet, its host star, and the observer on Earth, which does not happen a lot. Lastly, Astrometry is particularly good at detecting the planets which are around other stars, especially those which are massive and are close to their host stars. Additionally, astrometry is also capable of detecting planets with very long orbital periods, as well as planets that are located at great distances from their host stars.

In conclusion, each method has its own strengths and weaknesses, and astronomers often use a combination of methods to detect and study exoplanets. As technology advances and new techniques are developed, we can expect to learn even more about these fascinating worlds beyond our solar system.

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