Analysis of Planet Searching and Detection: Radial Velocity, Gravitation Microlensing and Transiting

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Abstract. As a matter of fact, planet searching plays a critical role in astrophysics and cosmology. This paper focuses on three main methods of planetary search and detection: radial velocity, gravitational microlensing, and transit. First, this study introduces the background and significance of planetary search and detection, pointing out the importance of planetary detection for understanding the origin of the universe and the existence of life. Then, the article describes seven exoplanet detection methods and what they can detect. It explains the principles, instrumentation, and technical details of radial velocity method, transit method, and gravitational microlensing method, and cite some successful cases. Finally, this study looks forward to future directions of planetary search and detection, including the utilization of new observational equipment and techniques to improve detection efficiency and accuracy, and the search for more Earth-like planets and possible life existence. These results offer guideline for advancing the development of planetary detection.

Keywords: Planet searching; radial velocity; gravitational microlensing; transiting.

1. Introduction

People have been exploring the universe in more and greater depth as science and technology have advanced. In the past decades, astronomers have discovered the existence of exoplanets through observation and research [1-3]. In the past, it was widely believed that the solar system was the only place where planets existed; however, as science and technology advance, huamn beings are beginning to find more and more evidence that there are a large number of exoplanets in the universe. These planets are similar to the Earth, orbit around stars, and potentially have the right conditions for life to exist. This discovery has attracted much attention from the scientific community and has become one of the hotspots of astronomical research. The detection of exoplanets is one of the most important topics in astronomical research, and is of great significance to the understanding of the origin of the universe, and the special properties of the Earth [2]. Through the study of exoplanets, one can better understand the formation and evolution of the universe, search for planets suitable for the existence of life, and explore the special properties of the Earth in depth.

In 1992, two astronomers, McMalone and Wolf, discovered three planets around a pulsar named PSR B1257+12. This is the first discovery of an exoplanet in human history. The first detection result of planets discovered in the main sequence star system appeared in 1995. Swiss astronomers Michel. Mayor and Queloz discovered a giant planet, Pegasus 51b, which orbits once in a 4-day period near Pegasus 51 using radial velocity method. This is the first exoplanet to orbit a sunlike star, marking the beginning of the era of exoplanet exploration; Since then, the detection methods and technologies for exoplanets have been continuously developing and becoming increasingly mature [4]. Since the discovery of the first exoplanet in 1992, more than 400 exoplanets have been discovered by humans before the launch of the Kepler Telescope in 2009 [5]. In 2000, Henry et al. and Charbonneau et al. independently discovered the exoplanet HD 209458 b, which is similar to 51 b in the constellation Pegasus and also orbits a sunlike star [6, 7]. In 2007, scientists discovered a planet called Gliese 581c, which is located in the habitable zone and may contain liquid water, making it one of the important targets for humans to search for extraterrestrial life. In 2009, the Kepler Telescope was launched to monitor the luminosity changes of approximately 500000 stars and search for potential candidate targets for exoplanets; In order to carry out a larger scale exoplanet search, in April 2018, TESS (transiting exoplanet survey telescope), the successor to the Kepler telescope, was launched and planned to conduct exoplanet search and research throughout the sky. As of now, astronomers have discovered and confirmed over 5000 exoplanets through the use of different detection instruments and methods [2].

The motivation for this paper is to synthesize and compare planetary search and detection methods in order to achieve a more comprehensive understanding and exploration of planetary systems in the Universe. This paper will focus on three exoplanet detection methods, namely the radial velocity method, the gravitational microlensing method, and the transit method. By studying and analyzing these three methods, their advantages and disadvantages can be revealed to provide a reference for the research in the field of planet search and detection. In the following chapters, the currently available methods for exoplanet detection will first be briefly introduced along with what each method can detect. Next, three chapters are devoted to the radial velocity method, the gravitational microlensing method, and the transiting star method. This will include an introduction to the principles of these three methods, their instrumentation, and the results of recent detections. Finally, the limitations of current exoplanet detection and research and the outlook for the future are briefly outlined, and the text is summarized.

2. Basic Descriptions

So far, there are seven main methods for detecting exoplanets. They are astrometry method, direct imaging method, radial velocity method, transit method, gravitational microlensing method , pulsar timing variations, and special relativity method [8-10].

Astrometry, which precisely examines the motions of stars to calculate the position of planets tugged by their gravitational attraction, is the first technique one developed for finding exoplanets. The advantage of astrometry methods is that they can calculate planetary masses more accurately and are particularly sensitive to planets with large orbits. Using astrometry, the masses and orbital parameters of exoplanets can be determined more accurately, especially long-period planets. However, this method requires a very high degree of precision and requires years or even decades of observations to confirm the results.

The direct imaging method is to take direct pictures. The benefit of this approach is that it enables direct measurements of the size and spectra of planets. To gather the most direct and comprehensive information about an exoplanet's luminosity, temperature, atmosphere, orbit, and other characteristics, this procedure is similar to taking a "ID photo" of it. However, this technique needs the planet's volume to be sufficiently huge and not too close to its parent star in order to prevent being obscured by the parent star's light, necessitating extremely precise instrumentation. and there is almost no way to carry out such an observation on the ground, so this method is more dependent on space observation.

Unlike the direct imaging method, most exoplanets are discovered by indirect methods. One fruitful indirect method is radial velocity method, which is based on the Doppler effect, which means that the spectral lines of a celestial body will be red shifted or blue shifted as it moves closer or farther away relative to the observer at a certain speed. As a planet moves around a star, its gravitational pull causes the star to move slightly as well, resulting in a change in the radial velocity of the star. The presence of planets and their orbital parameters can be inferred by measuring the change in the radial velocity of the star. The mass and cycle of the planet can be inferred from the detection of velocity fluctuations as tiny as 1 meter/second by modern spectroscopic sensors.

Transits are when an exoplanet passes between its parent star and the Earth and the planet blocks some of the light from the star, causing a slight dimming of the star's brightness as one observes it. This minor variation in light can be used to infer the existence of an exoplanet. Since transits are uncommon, it is essential to keep an eye on as many stars as possible in order to find as many exoplanets as possible. This method is simple and requires relatively low photo-metric accuracy. After a long period of monitoring of the target sources where exoplanet transits may occur and obtaining the corresponding light curves, some of the basic parameters of the exoplanet can be obtained, such as the planet's radius, orbital period, etc., if the decrease in luminosity due to transits can be explained.

The gravitational microlensing method is a method of detecting exoplanets by utilizing the gravitational deflection of light. It is an indirect method of detection, in which the presence or absence of exoplanets is inferred by observing the bending of light. The principle of the gravitational microlensing method is that when a star or galaxy passes through the path of light, its gravity deflects the light, creating a lens-like effect. If there is an exoplanet in the path of the light, its gravity will also have an effect on the light, further altering its path. By observing this deflection of light, the presence or absence of an exoplanet can be inferred. By observing gravitational microlensing events one can infer the mass of the exoplanet. In addition to this gravitational microlensing can be used to measure the orbits and spectra of exoplanets.

Pulsar timing variations is a method of detecting exoplanets by measuring the period variations of pulsars. Pulsars are a special type of star that have very stable rotation periods, usually on the order of milliseconds. When there are planets around a pulsar, the gravitational pull of the planets can have a small effect on the pulsar's rotation period, resulting in a change in the pulsar's period. By accurately measuring the change in the pulsar's period, one can infer the presence of planets and some of their basic parameters. What can be detected by the pulsar timing method include the mass of the planet, orbital parameters and spectral characteristics.

The special relativity method is a method of detecting exoplanets based on Einstein's theory of special relativity, which determines the existence and nature of planets by observing changes in the frequency and energy of light. Detectables by the special relativity method include gravitational redshifts, gravitational time delays, and gravitational lensing effects.

3. Radial Velocity

The radial velocity method is one of the most accurate methods for detecting exoplanets to date. The radial velocity method is a typical kinetic method, and its principle is mainly as given in Fig. 1.The Doppler effect is the underlying theory behind this procedure, hence the term Doppler effect method. A planet's parent star feels the pull of the planet as it revolves around it. And the star's emission spectrum is correspondingly red shifted and blue shifted, with the spectral lines in the spectrum of the primary star blue shifted when the primary star is moving towards the Earth in the direction of the line of sight, and red shifted when the primary star is moving in the direction of moving away from the Earth. From this, the radial velocity of the star (the speed of motion toward or away from Earth) can be deduced. The method of detecting the Doppler effect caused by such exoplanets is the radial velocity method. The basic principle of radial velocity detection is similar to that of astrometry, which indirectly detects changes in the motion or position of the host star caused by an exoplanet. The current detection accuracy of this method is on the order of 1 m/s, but considering that the velocity of the Earth towards the Sun is only on the order of 0.1 m/s, it is still not realistic to use it to detect super-Earths such as the Earth, which are in the habitable zone of yellow-white main-sequence stars. Furthermore, this method can only give a lower limit on the mass of the planet Msini, where i is the angle between the axis of the planet's rotational orbit and the direction of the line of sight, and M is the planet's mass.

In the radial velocity method, the main instrument used is a high-resolution spectrograph. This instrument measures the frequency variations in the spectra of stars to obtain the radial velocity variations of the stars. By observing the star's spectrum over a long period of time, one can detect small radial velocity variations caused by the planet and thus determine parameters such as the planet's mass, orbital period and orbital eccentricity. One of the representative instruments for detecting exoplanets using the radial velocity method is the High Accuracy Radial velocity Planet Searcher (HARPS), which is mounted on top of the European Southern Observatory's (ESO) telescope with an aperture of 3.6 meters (the aperture of the telescope refers to the diameter of its light-gathering mirrors). In 1995, Michel Mayor and Didier Queloz from the University of Geneva discovered 51 b Pegasus (51 Pegasi b), the first exoplanet orbiting a sun-like star, using the radial velocity method. This discovery won the 2019 Nobel Prize in Physics. In recent years, the radial velocity method has successfully detected many exoplanets. For example, in 2009, scientists used this method to discover HD 209458 b, an exoplanet with a mass similar to that of Jupiter. And to date, astronomers have discovered 1,005 exoplanets, or about 18.37% of the total, using the radial velocity method. Of particular note, astronomers used this method to confirm in 2016 that the nearest star to the solar system, Proxima, has an exoplanet, Proxima b, which has a lower mass limit slightly larger than the Earth.

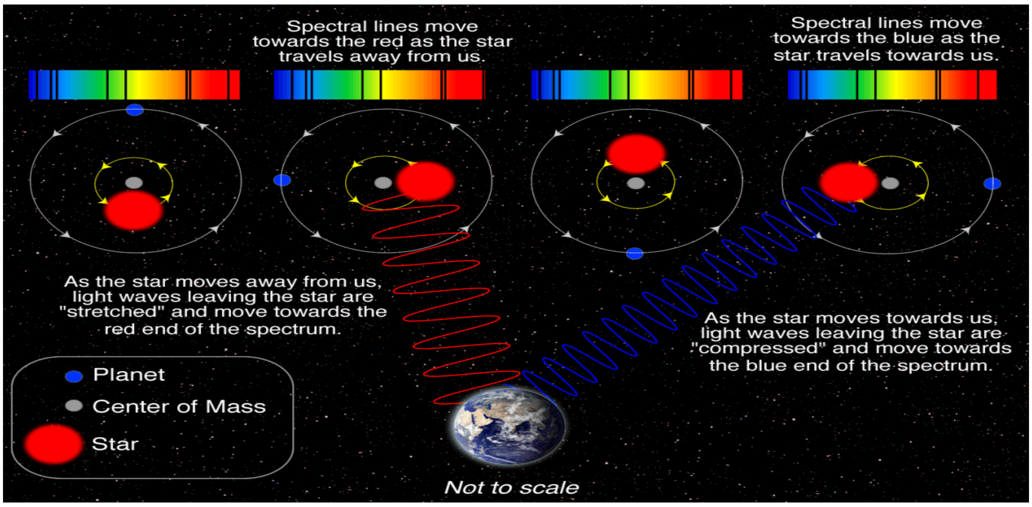

Fig. 1 A sketch of the radial velocity.

4. Transit

The transit method is a method of detecting planets by observing changes in the star's brightness. Periodic variations in the star's brightness result from planets periodically passing in front of their parent stars, blocking some of the star's light. This change in brightness is called a transiting star phenomenon. By observing and analyzing transiting stars, one can deduce the existence and some basic properties of planets. In the transit method, one first needs to choose a suitable star for observation. Usually, the star chosen should be bright and stable so that its brightness variation can be measured accurately. At the same time, the star needs to be at a moderate distance from the Earth so that the probability of the planet passing in front of the star is high. Once the target star has been chosen, one can start making observations. Observations usually require the use of specialized telescopes and high-precision photometers to measure the brightness of the star. Observations usually last for hours or even days so that the moment when the planet passes in front of the star can be captured. The observed data need to be processed and analyzed in a series of steps to produce accurate results. First, one needs to calibrate the observed brightness data to remove interference caused by factors such as atmospheric conditions and instrumental errors. Then, one can determine the presence of planets and some basic parameters by comparing the observed brightness variations with the predictions of theoretical models. A sketch is shown in Fig. 2.

The reduction in stellar brightness due to transits is of very small proportions and therefore requires a very high degree of instrumental measurement accuracy. The implementation of the transit method requires the use of high-precision photometers to measure the change in stellar brightness. These photometers usually use photodetectors to measure light intensity and filters to select a specific wavelength range. Correction of the background light and filtering of noise is also required to improve the accuracy of the measurements. Exoplanet discovery using this method is represented by the Kepler space telescope and its successor, the Transiting Exoplanets Survey Satellite (TESS), both of which have a very wide field of view and can simultaneously monitor the brightness of a large number of stars, thus efficiently filtering out stars with cyclic changes in brightness. stars with periodic changes in brightness. Astronomers use the data to determine whether such variations are caused by exoplanet transits.

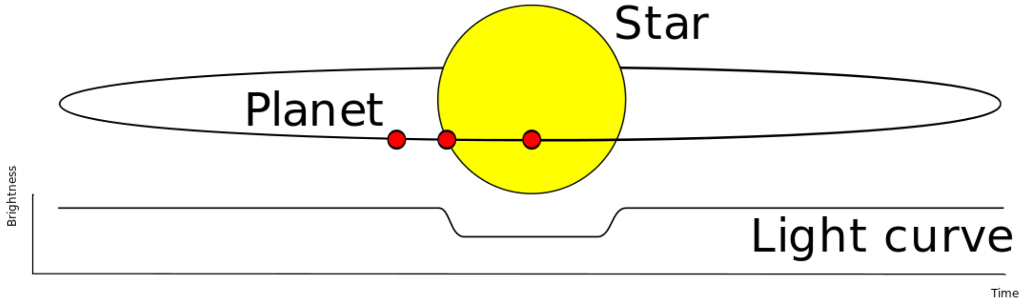

Fig. 2 A Schematic diagram of the principle of the transit method of exoplanet detection.

In recent years, with the advancement of technology, important breakthroughs have been made in the transit method. For example, using high-precision photometers and precise data analysis methods, scientists have successfully detected many exoplanets and measured their sizes, orbital periods, and other parameters. To date, astronomers have discovered at least 3,925 exoplanets, or about 71.74% of the total, using the transit method. For example, in 2011, scientists used this method to discover Kepler-22b, an exoplanet with a mass like that of Earth. And more than 2,700 of these exoplanets have been identified from the Kepler detection data. The transit method has also given rise to the transit timing method. It is based on the principle that the period of planetary transits is fixed and precise. If a star is transiting with an imprecise period, it is possible that another planet is interfering with its orbit, and the presence of the latter can be determined accordingly. Using this method, astronomers have discovered 23 exoplanets.

5. Gravitational Microlensing

The gravitational microlensing method is a method of detecting planets by utilizing the bending of light by gravity (seen from Fig. 3). According to Einstein's General Theory of Relativity, mass bends the surrounding space-time, thus deflecting the path of light. When a planet passes between us and a distant star, its gravity bends the star's light, creating an optical lens that allows us to detect the planet's presence. The principle of the gravitational microlensing method is based on the imaging principle of an optical lens. When a star and a planet are very close to each other, the gravitational pull of the planet bends the light from the star to form a bright halo or arc. By observing the changes in the shape and brightness of this halo or arc, one can infer the existence and some basic properties of the planet. The disadvantage of the microgravitational lensing method is that it cannot be repeated because the star drifts away and never looks back, but it has the advantage of a clear signal.

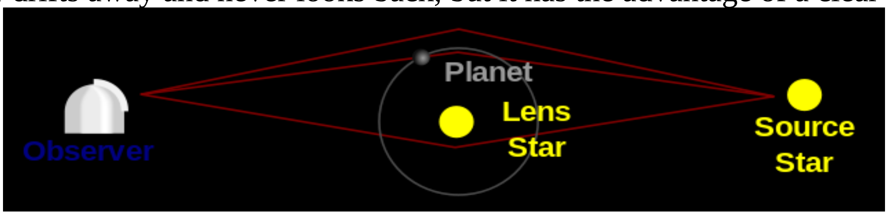

Fig. 3 Schematic of the gravitational microlensing method of exoplanet detection

In the gravitational microlensing method, commonly used instruments include high-precision telescopes and sensitive photometric equipment. The telescope is used to observe the position and brightness variations of the star behind it, and the photometric equipment is used to measure the brightness variations of the star. Continuous monitoring of the brightness of the star is needed to detect changes in the halo or arc during the observation. Precise measurements of the shape of the halo or arc are also required to obtain information such as the mass and orbital parameters of the planet. In recent years, with the advancement of technology, the resolution and sensitivity of the instruments have been significantly improved, making the gravitational microlensing method more accurate and reliable for detection. The representative instruments for the search for exoplanets using the microlensing method are the Optical Gravitational Lens Experiment (OGLE) and the Korea Microlensing Telescope Network (KMTNet). The former is carried out by a telescope with an aperture of 1 meter, followed by a telescope with an aperture of 1.3 meters, and the latter by three telescopes with an aperture of 1.6 meters. To date, astronomers have discovered 212 exoplanets, or 3.87% of the total, using the microgravitational lensing method. For example, in 2015, scientists used this method to discover OGLE-2014-BLG-0124Lb, an exoplanet with a mass similar to that of Earth.

In summary, these three methods are currently commonly used methods for planetary search and detection, and have a wide range of applications. With the advancement of technology, these three methods have made remarkable progress and discovered a large number of exoplanets. These findings significantly affect how one thinks about planetary systems and the beginning of life in the universe. Although there are still some limitations, with the continuous development and improvement of observational techniques, they will continue to reveal more planetary mysteries in the Universe to us.

6. Limitations and Prospects

The depth of human investigation of the universe has increased along with the advancement of science and technology. In the past decades, one has discovered many exoplanets, but the current exoplanet detection still has some limitations. First of all, the current exoplanet detection mainly relies on three methods: radial velocity , transit and gravitational microlensing. Each of these methods has its own advantages and disadvantages, but they all have a common limitation, that is, they can only detect a part of the planets. Due to the limitations of the principles and instruments of these methods, one can only detect those planets that are closer to the star, have larger masses, or have orbits that deviate more from the star. Second, the current exoplanet detection is also limited by the observation conditions. Due to the interference of the Earth's atmosphere, one can only detect planets under certain observing conditions and one cannot obtain detailed information about the planets, such as their atmospheric composition, temperature, and so on. In addition, the current exoplanet detection is limited by technology. Although one has achieved some important results, the current technology can not meet the needs for planet detection. For example, one can only detect the existence of planets, but cannot directly observe the surface or atmosphere of planets. To summarize, the current exoplanet detection has some limitations. Besides, one still needs to further improve and develop detection methods and technologies to better understand the planets in the universe. Only by overcoming these limitations can one has a more comprehensive understanding of the universe and reveal the origins and evolution of the planets.

With the continuous development and progress of science and technology, the field of planetary search and exploration will also usher in a broader development prospect. In the future, one can expect progress and breakthroughs in the following aspects. First, with the continuous improvement of detection technology, one can foresee that the precision and accuracy of planetary detection will be significantly improved. Second, future planetary detection will pay more attention to multi-band observation and analysis. In addition, future planetary exploration can pay more attention to the study of the surface characteristics and geological structure of exoplanets. Currently, planetary exploration mainly focuses on the mass, orbit and atmosphere of planets, but has little understanding of the surface characteristics and geological structure of planets. In the future, through higher-resolution observations and more accurate data analysis, one can study in-depth the geomorphology, crustal motion and geological evolution of planets, so as to better understand the evolutionary history of planets and the possibility of extraterrestrial life. One can also explore the atmospheric composition, temperature distribution and the possibility of life on exoplanets through more precise observations and more in-depth studies. This will help us to better understand whether other life forms exist in the universe and the origin and evolution of life outside Earth. In conclusion, planetary search and exploration will face more challenges and opportunities in the future. Through continuous efforts and innovations, scholars are expected to make more breakthroughs and discoveries, and contribute more to human knowledge and understanding of the universe.

7. Conclusion

To sum up, this study focuses on three methods for planetary search and detection analysis: radial velocity method, transit method, and gravitational microlensing method. First, the paper describes the background of planetary detection and the seven exoplanet detection methods and what they can detect. The article then focuses on a basic description of the three main methods, including their principles, instrumentation, and detection results in recent years. Next, this study discusses the limitations of current exoplanet detection, including technological constraints and limitations of observation conditions. This study then loosk ahead to future directions, including more precise detection methods and a wider range of detection targets. The importance and challenges of planet search and detection analysis are emphasized and directions for further research are proposed. Finally, the full paper is summarized. Overall, planetary search and detection is a field full of challenges and opportunities. Radial velocity, transit , and gravitational microlensing, as the main detection methods, have made important progress in recent years. However, further research and technological innovations are still needed to address the current limitations and to reveal to us more about the mysteries of planets in the Universe.

References

[1] Seagar S. Exoplanets. University of Arizona Press, 2011.

[2] Spiegel D S, Fortney J J, Sotin C. Structure of exoplanets. Proceedings of the National Academy of Sciences, 2014, 111(35): 12622-12627.

[3] Mayor M, Frei P Y. New worlds in the cosmos: the discovery of exoplanet. Cambridge University Press, 2003.

[4] Jenkins J M, Borucki W J, Koch D G, et al. Discovery and Rossiter–McLaughlin Effect of Exoplanet Kepler-8b. The Astrophysical Journal, 2010, 724(2): 1108.

[5] Jin Y, Yang L, Chiang C E. Identifying exoplanets with machine learning methods: a preliminary study. arXiv preprint arXiv:2204.00721, 2022.

[6] Muñoz A G. Physical and chemical aeronomy of HD 209458b. Planetary and Space Science, 2007, 55(10): 1426-1455.

[7] Snellen I A G, De Kok R J, De Mooij E J W, et al. The orbital motion, absolute mass and high-altitude winds of exoplanet HD 209458b. Nature, 2010, 465(7301): 1049-1051.

[8] Wright J T. Radial velocities as an exoplanet discovery method. arXiv preprint arXiv:1707.07983, 2017.

[9] Sucerquia M, Alvarado-Montes J A, Zuluaga J I, et al. Scattered light may reveal the existence of ringed exoplanets. Monthly Notices of the Royal Astronomical Society: Letters, 2020, 496(1): L85-L90.

[10] Dai Z, Ni D, Pan L, et al. Five methods of exoplanet detection. Journal of Physics: Conference Series. IOP Publishing, 2021, 2012(1): 012135.