Analysis of Extra-Planets Searching and Detection Approaches: Radial Velocity, Transition and Gravitational Microlensing

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Abstract: The search for exoplanets has become one of the most dynamic and rapidly advancing fields in modern astronomy. Understanding these distant planets expands our knowledge of planetary systems and provides crucial insights into the formation and evolution of the solar system. This study compares three major exoplanet detection techniques, i.e., radial velocity, transit photometry, and gravitational microlensing. By examining their detection principles, strengths, and limitations, the study provides a theoretical foundation for selecting appropriate methods under different observational conditions. Radial velocity is particularly effective for detecting massive planets around nearby stars and measuring planetary masses; transit photometry is well-suited for identifying smaller, close-in planets; and gravitational microlensing is uniquely capable of revealing distant and low-mass planets, including those beyond the snow line. Given the complementary nature of these techniques, the paper highlights the growing importance of a multi-method approach to improve detection accuracy and broaden the scope of exoplanet discovery. This comparative framework offers practical guidance for researchers in choosing optimal detection strategies based on specific scientific goals and target characteristics.

1 INTRODUCTION

Humans have started to investigate planets in very old history in many cultures. In ancient societies, people's findings of planets are expressed by myths, large-scale devices, calendars, etc. For example, the Popol Vuh of the ancient Maya counts the creation of the "sky-earth", Stonehenge in England (~3000 BCE) was designed according to celestial events. In 1543, Copernicus first proposed that planets move in orbits around the Sun. Then Galileo's planetary observation and Kepler's laws of planetary motion were discovered, which was incorporated into a new physical explanation of the planets. In 1687, Newton succeeded in describing the universal force of gravity mathematically presenting that the movements of planets are the results of a gravitational relationship (Shindell, 2023). The research before the 20th century focused on the motion laws of planets. With modern techniques' developments, the detection of planets' meanings varies. For example, discovering and exploring habitable planets and searching for possible extraterrestrial lives, like the CHES's project (Ji, et al., 2022), detecting extrasolar planets to understand the origin of the solar system, like the Orion project (Black, 1980), or just for the reason of deepening the understanding of planetary systems, like the Kepler mission (Borucki, et al., 2007).

Despite the breakthrough in astronomy, the detection of planets would promote the development in related areas, including geology, planetary science, astrochemistry, astrobiology, and atmospheric science (Zhou, et al., 2024). According to the Encyclopaedia of Explanatory System websites, 7423 planets have already been discovered in different methods by March 16, 2025. As the amounts of discovered planets increased, it provided researchers with a deeper understanding of the diversity of the cosmos. Researchers classified different planet types due to their physical properties and orbital (Muresan, 2025). Despite the remarkable achievements that researchers have made, there are still several critical questions unsolved. More reliable and efficient detection is needed, to break the challenges and answer the questions.

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Although different methods of planetary detection have been proposed and practiced, such as radial velocity, transit, microlensing, and direct imaging, the different techniques have significant differences in many aspects, which makes it difficult for researchers to select a suitable method. Moreover, with fast development in the planetary detection field, more findings and technologies are presented, and a comprehensive review is needed to organize the information on different methods of planetary detection.

The research aims to analyse the details of 3 main methods of planetary, transition, radial velocity, and gravitational microlensing, explain the advantages, limitations, and application scenarios of each method by conducting existing literature, helping researchers choose the proper method when given different conditions.

2 DESCRIPTIONS OF PLANET SEARCHING

Planet searching covers a great range of physical quantities, including quantities about orbital, mass, atmosphere, inner structure, fluxes, and planetary surfaces. For extrasolar planets, researchers based mostly on radial velocity measurements, transition measurements, imaging and microlensing to gain planetary information. In early planetary detection discovery before 2014, it was the most common to use the measurements of radial velocity. However, with equipment's promotions, researchers can detect the planets with longer distances by using transition information. Until January 21st, 2025, 5819 exoplanets were confirmed, with about 74% detected by using the transition method, 19% by measuring the radial velocity, and 4% by using gravitational microlensing. Despite the other methods were not as common as the three methods above, they still helped with about 1% of planets were detected for direct imaging, 0.6% for transition time variation, and 0.05% for astrometry (Muresan, 2025).

3 RADIAL VELOCITY

In 1995, Machel Mayor and Didier Queloz discovered the first exoplanet orbiting a sun-like star using the radial velocity method and named it 51 Pegasi b. Although the information provided by radial velocity signals is limited, RVs are very successful at detecting exoplanets. The radial velocity is based on the Doppler shift effect on the spectrum of a star when the planet and its host star are rotating around the same mass centre. This orbit makes the star appear to wobble in the sky. Although this change in position can be detected using the astrometry method, it can be more sensitive for researchers to determine the shift in wavelength of the starlight, due to the periodic Doppler effect when the star rotates around the mass centre of the system. When the star approaches the receiver, the frequency of light will increase, then its spectrum will move towards the blue side, and the shift is therefore called the blue shift. Similarly, the spectrums move towards the red side for being away from the observer as shown in Fig. 1 (Muresan, 2025). By measuring the frequency change in a star's spectrum, researchers can determine how fast the star moves toward or away from the observers due to the gravitational interaction between the star and orbital planets.

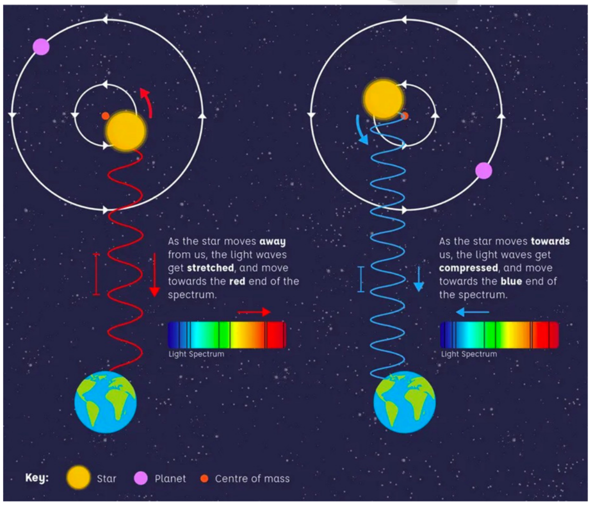

Figure 1: A sketch of the Doppler effects.

Because of, the star's orbit, the distance from the system's mass center to the star will increase as the ratio of the mass of the star and planet approaches 1, the shift is more obvious. The method thus is more sensitive in the detection of large-mass planets (Brogi, et al., 2013; Lovis & Fischer, 2010). That's also the reason why the first exoplanet is 51 Pegasi b because it is a gas giant and typed in hot Jupiter with a minimum mass of about 0.47 times that of Jupiter. However, it can also be used for terrestrial planets although it is still very challenging. For example, Nieto & Díaz succeeded in training a convolutional neural network algorithm to detect planets with a mass of about 4 times that of the Earth, even if the radial velocity is as low as 5 meters per second. However, the radial velocity method can only determine the minimum possible value of the planet's mass, since the orbital inclination is unknown. The measurements only cover the motion of the star along the line of sight, which means the radial velocity signal can be weakened if the angle between the sight line and orbit is large. Another limitation is that the interference from stellar activities can also affect the spectrum of starlight. Stellar activities like sunspots and flares can cause spectral line shifts, besides some of these activities are periodic as well. So, it will be hard to avoid this kind of interference. With the improvement of techniques, researchers are now trying to mitigate this issue (Zhao, et al., 2024). Besides, the method may be limited to determining the shift of planets with high speed because the fast movement broadens their spectral line and makes the determination not precise enough. In summary, the radial velocity method is more likely to be used in the detection of inactive, cool, and slowly rotated stars with typical spectrum types of F, G, and K.

The instruments used in the radial velocity method are highly specialized now, which can achieve the high precision needed to detect the tiny Doppler shifts caused by orbiting planets. Spectrometers are the most common instrument used in radial velocity. It detects shifts in the spectrum from stars. There are two common types of spectrometers used in radial velocity: echelle spectrometers like HIRES at Keck Observatory and fiber-fed spectrographs like FEROS at the European Southern Observatory (ESO). Spectrometers are usually equipped on large telescopes that collect and focus the light from distant stars. The size directly impacts the amount of light gathered and the resolutions of observations. To provide a precise measurement, it is also important to keep the optical systems stable. The equipment is usually placed in a temperature-controlled environment to minimize the errors in the spectrum measurements. As technology advances, future instruments aim to push the precision further to reliably detect Earth-like planets around Sun-like stars.

Although the number of exoplanets found by radial velocity is not as much as it is in the history of recent years, the contribution of the method can still be important. Besides redial velocity has achieved an extreme precision of 10 $cm\ s^{-1}$, which means the method can be used for detecting exoplanets with fewer limitations. Besides, recent research is intense to combine measurements of other methods to get more detailed and accurate information (Hara & Ford, 2023). Future detection using radial velocity can deserve the researcher's expectations.

One specific example is the detection of Barnard's Star b, using a high-precision spectrometer ESPRESSO, detected by Jonay González Hernández's team in 2024. Barnard's Star B is a red drawl with a distance of 6 light-years from Earth. Because its minimum mass is relatively low, about 0.3 times that of Earth, it is hard to detect without a high-precision instrument. The detection of Barnard's Star B may demonstrate that if the precision gets higher, it is possible to use the radial velocity method to search for more exoplanets.

4 TRANSITS

The emergence of the transit method is a significant event in exploring planets. Since, 1631, Pierre Gassendi first observed the transition of Mercury across the Sun (Fisher, 2005), the transit method was used to study the subjects in the solar system. In 1999, astronomies succeeded in determining the existence of exoplanet HD 209458b using the transit method (Snellen, et al., 2010). It was proved to be valid in the detection of exoplanets. The transit method has helped researchers detect more than 4000 exoplanets and become the most crucial technique for discovering the universe. As technology progresses, the transit method will still play an irreplaceable role in exploring exoplanets.

When a planet transits the star, a small part of starlight cannot pass through the planet, and, thus, the measurement of its magnetoelectronic wave will experience a significant drop in its light curves, which shows the star's fluxes over time. The light curve shows a "U" shaped dip when the transit occurs. As the planet starts to enter the disk of the star, the light curve begins to fall until the whole body of the planet enters the disk. During the time that the whole planet is in the star's disk as the example of HD 209458 b shown in Fig. 2 (Haswell, 2010), the light curve would stay at a relatively low value before a part of the planet moves off the disk, which is directly related to the size of the planet and the star. Then, the light curve would rise gradually back, until the planet is totally off the disk (Deeg & Alonso, 2018).

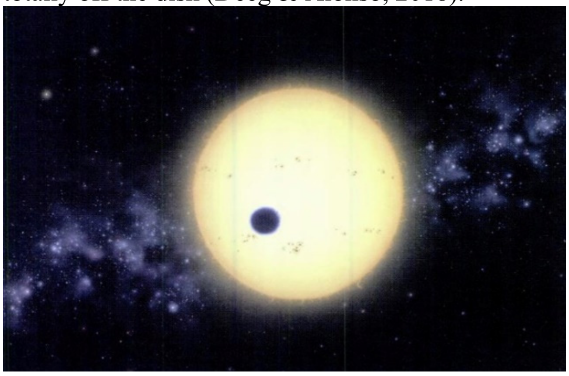

Figure 2: The impression of the transit of HD 209458 b across its star (Haswell, 2010).

The transit method provides valuable information about the planet, such as its size, and orbital period. Since the brightness dip in light curves' relation to the sizes of planets, researchers can determine planets' sizes relative to the stars by analysing the depth of the transit depth. If the planet's orbit is stable, the period of the planet can be determined by measuring the time between each transit event (Nesvorný & Morbidelli, 2008). In some cases, due to some compositions in the planets' atmospheres can absorb magnetoelectronic waves of wavelengths, by analysing the spectral changes during the transition researchers can study the temperature, compositions, and structure of their atmosphere (Sing, 2018).

The transit method can be considered the most successful method to detect exoplanets, for it allows the discovery of many exoplanets with a great quantity of data, especially when it is combined with the radial velocity method. It is highly efficient in terms of time and effort because the monitoring of a star's fluxes over time can be done continuously without interruption. Space telescopes like Kepler and TESS, it can observe hundreds of thousands of stars' fluxes concurrently, which means the method can be used for large-scale detection. The precision of Kepler and TESS allows researchers to detect a minimal variation in light curves. Then, the method is good for detecting Earth-like or even smaller exoplanets, which other methods might miss (Winn, 2024; Bruno & Deleuil, 2021). The transit depends on stable, wide-field, high-cadence detectors, most effectively applied in space to avoid atmospheric effects. Missions like Kepler and TESS have significantly expanded the known population of exoplanets. The refinement of both instrumental sensitivity and observational strategies will ensure that transit-based surveys remain at the forefront of exoplanet detection and characterization. These instruments, especially when paired with radial velocity and atmospheric spectroscopy, are central to the future of exoplanet science.

While the transit method is highly successful in detecting exoplanets, several limitations and challenges exist. One of the limitations is that the planet's orbit must be aligned in the plane of its star and the Earth. That means one can only observe a fraction of exoplanets aligned along our line of sight. Besides, to confirm the planets' existence, researchers need to observe several times of transitions, which might need several years of observation if the orbital period of the planet is relatively long. The transit methods can also be affected by a variety of stellar activities including star spots, stellar flares, and stellar pulses causing fake positives.

TOI-2180 b1 is a gas giant exoplanet that was discovered and confirmed to exist in 2022 using the transit method with TESS. It has a period of 260 days with a moderate orbital eccentricity of 0.37. The planetary existence was then validated by the radial velocity method (Dalba, et al., 2022).

5 GRAVITATIONAL MICROLENSING

The gravitational microlensing is an astrophysical phenomenon that occurs when the light from a distant star travel through the gravitational fields of a massive object, such as stars and black holes. The gravitational field with great strength would act as a lens and magnify the magnetoelectronic waves. This effect is a consequence of Einstein's theory of general relativity, which predicts that light will bend around a massive object as depicted in Fig. 3 (Zakharov & Sazhin, 1998). In the situation where the lensed star is perfectly aligned with the massive object, the ring image would become apparent (Zakharov & Sazhin, 1998). The effect can also be observed by analysing the light curve. When the light travels through the lens of the gravitational field, the light curve would experience a sharp increase in fluxes. The magnification depends on the alignment of the light source and lens and the peak of fluxes is generated now when the lens is closest to the line between the earth (observer) and the light source. In the field of exoplanet detection, massive exoplanets would act as the microlensing. The planet's effect on the microlensing light curve would create a characteristic increase in the fluxes, and the presence of the planets can be determined in this method, in the case that the orbit of the planet is nearly perpendicular to the Earth, which makes the radial velocity and transit method hard to practice.

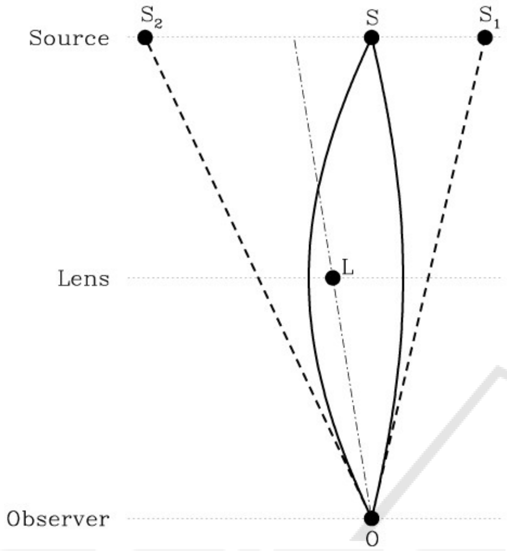

Figure 3: The massive object acts as lens L located between source S and observer O produces two images S1 and S2 of the background source (Zakharov & Sazhin, 1998).

The gravitational method has helped to find over 400 exoplanets. However, the gravitational microlensing method comes with several significant limitations, particularly because of its rarity. Since the microlensing events require a very precise alignment between a ground source, the lensing objects, and the observer. Since the alignments happen randomly, it is hard for researchers to predict the microlensing events long in advance. Thus, to catch the potential events, researchers must monitor millions of stars continuously. Unlike the radial velocity and transit method, gravitational microlensing events are mostly single-time measurements. This makes it almost impossible to refine the measurements of planets in followed observations, once the lens and source have moved out of alignment (Wambsganss, 1998; (Rektsini & Batista, 2024).

Observing gravitational microlensing events requires specialized instrumentation capable of continuously monitoring dense star fields with high photometric precision. These telescopes provide the high cadence and continuous observation necessary to capture the short-lived light curve changes caused by microlensing planets. One example is the project Korea Microlensing Telescope Network（KMTNet), which operates telescopes in Chile, South Africa, and Australia. The KMTNet telescope is equipped with high-sensitivity CCD cameras to play a central role in detecting the possible gravitational microlensing method in the universe (Kim, et al., 2016).

MOA-2022-BLG-249Lb, a nearby super-Earth exoplanet 2000 par seconds away from the Earth, was detected via gravitational microlensing in 2022. The planetary mass was determined to be about 4.83 times that of the Earth. It orbits a host star with a mass of 0.18 times that of the sun. The gravitational microlensing event happened with a brightness deviation of 0.2 magnitudes during about 1 day (Han, et al., 2023).

6 COMPARISON, LIMITATIONS, AND PROSPECTS

Despite the three methods mentioned above being widely and commonly used in the exploration of exoplanets, each method has its strengths, limitations, and ideal use conditions. The radial velocity method is particularly effective for detecting massive planets in orbits with a small radius, but it is limited to being sensitive in the search for small planets, particularly for those far from their stars or in multi-planet systems. Another limitation is that the radial velocity method needs highly stable spectrums to operate, which means without stability the spectral shifts could be mistaken for stellar activities.

Transits are highly effective for detecting small planets, even those Earth-sized, but the method requires near-perfect alignment between the planetary orbit and our line of sight. For this reason, many planets may be undetected because of their angles. A critical aspect of the transit method is the need for high-precision photometric measurements and continuous monitoring of millions of stars over extended periods.

Gravitational microlensing is a less common but powerful method to detect farther exoplanets. However, microlensing events do not repeat, making confirmation and further studies challenging. A single event caused by the presence of a planet orbiting the lens star often lasts only a few hours. Capturing such short-lived deviations requires observations every few minutes which strongly demands telescope scheduling, data processing, and instrument readiness.

The paper primarily focuses on three widely used exoplanet detection methods: radial velocity, transit, and gravitational microlensing. However, the paper does not discuss other detection methods such as direct imaging and astrometry. Despite their effectiveness in specific conditions, they do not belong to the main scope of the paper. Future research is expected to combine and compare the results from multiple observational methods. By integrating different methods, researchers can gain a more comprehensive understanding of exoplanetary discovery. This multi-method synergy not only improves the confirmation of planetary candidates but also expands the diversity of planetary types and environments one can detect.

7 CONCLUSIONS

To sum up, this research has examined and compared three of the most prominent exoplanet detection techniques: radial velocity, transit photometry, and gravitational microlensing, providing researchers theoretical basis for choosing proper methods in different conditions of exoplanetary detection. Each method offers distinct advantages. Radial velocity is best suited for detecting massive planets around nearby stars and confirming planetary masses; transit excels at identifying planets with lower masses and gravitational microlensing is uniquely effective for detecting distant planets. Given these complementary strengths and weaknesses, it is increasingly clear that the most effective strategy for exoplanet detection and characterization lies in the integration of multiple methods. By illustrating and comparing radial velocity, transit, and gravitational microlensing, the paper helps to clarify the roles played by these three most widely used methods and offers guidance to researchers in selecting optimal detection strategies for different scientific contexts.

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