# Probing Exoplanets Based on Transit, Radial Velocity and Direct Imaging

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Keywords: Exoplanet Detection, Radial Velocity, Transit, Direct Imaging.

Abstract: As a matter of fact, human beings have evolved step by step from primitive humans to nowadays, never giving up on exploring the universe. Since Soviet cosmonaut Yuri Gagarin took off on the Vostok 1 spacecraft, human began to explore the universe frequently. So far, preliminary progress has been made in the study of exoplanets. In reality, the exploration of exoplanets will have a profound impact on the development of human civilization, and may lead to the discovery of a second Earth suitable for human survival. With this in mind, this article will introduce some commonly used methods for discovering exoplanets, and provide a detailed introduction to the three most common methods and their principles, instruments, and related results. According to the analysis, this study summarizes the present problems and difficulties that limiting exoplanet detecting and looks ahead to the promising developments of planetary exploration in the future. These results provide a guideline in further discoveries of exoplanet.

## 1 INTRODUCTION

Earth is currently the only planet determined by humans to have life. Scientists have long hoped to discover other exoplanets outside the solar system that are fit for the existence of life. Ever since the first exoplanet has been discovered to be orbiting a sun-like star in 1992 (Mayor and Queloz, 1995). The exoplanet has an enormous breakthrough in the last 30 years. The search for exoplanets has become one of the most active topics in astronomy and astrophysics (Mamajek and Stapelfeld, 2024). Some typical important progress is summarized in Fig. 1 (Zhou et al., 2024).

The systematic observation and theoretical characterization of exoplanets have some scientific significant. First, it will greatly deepen people's comprehending of the past as well as future of Earth and the solar system, which is relevant to the future development of mankind. Secondly, the observations of exoplanets have provided critical data to test theories of the growth and evolution of the solar system, which has greatly improved the understanding of the derivations of the Earth and life. Thirdly, it will also have the potential to directly answer the major scientific question of whether humans are alone in the universe, and is a prerequisite for the search for habitable planets and even the establishment of extraterrestrial homes condition (Zhou et al., 2024).

Ever since the initial exoplanet was found in 1995, research into exoplanets has involved participation from every country. Both the second Kepler mission and NASA's Kepler mission proposals were seen as enormous successes (Borucki et al., 2010). The discovery of the first confirmed rocky exoplanet received a lot of media attention. Using this kind of process, 548 exoplanets emerged between 2009 and 2018. The most successful detection experiment to date is TESS, its successor and a representative instrument of the transit method. The world's optional telescope now, the Very Large Telescope of the European Southern Observatory (VLTESO) is used for planet discovery. Beyond technical constraints, its equipped ESPRESSO achieves 10cm/s precision and significantly improves detection accuracy (Pepe et al., 2014). The JWST Space Telescope is scheduled to launch in 2021 (JWST group, 2023). As of right now, JWST has accurately measured the composition of the atmospheres of some exoplanets (including $H_2O$, $CO_2$, and CO, $CH_4$), and has also discovered several wandering binary planetary systems. This planet system has majority of planets found beyond the solar system to date: 5,514 exoplanets had been found as of



Ma, L.
Probing Exoplanets Based on Transit, Radial Velocity and Direct Imaging.
DOI: 10.5220/0013043200004601

In *Proceedings of the 1st International Conference on Innovations in Applied Mathematics, Physics and Astronomy (IAMPA 2024)*, pages 247-252
ISBN: 978-989-758-722-1

September 10, 2023, primarily due to human competence in more than ten exoplanet methods of detection (Yock and Muraki, 2018).

This article aims to provide an overview of the most widely used exoplanet methods for detection currently in use, as well as display their principles and related instruments. The Section 2 will introduce the mainstream exoplanet detection methods and detectors. In Section 3, the study will concentrate on the principle of detection method of transit, related instrument and concrete detection results in detail. Section 4 will include specific for the particulars of the radial velocity, the relevant instrument, and its discovery outcomes. The measuring principle, instrument application, and significant advancements in direct imaging will be covered detailed in the fifth section. In Section 6, the current obstacles to exoplanet detection progress will be systematically evaluated along with the opportunities and challenges that lie ahead. The article will be summarized in Section 7 together with an optimistic outlook for exoplanet discoveries.

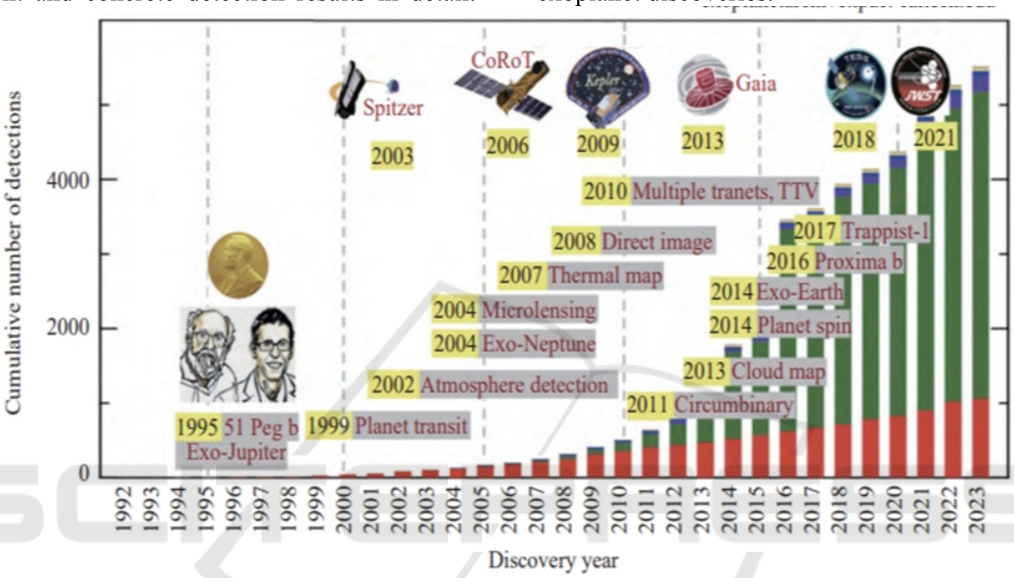


Figure 1: Important progresses and space telescopes in exploration of exoplanets (Zhou et al., 2024).

## 2 DESCRIPTION OF PLANET SEARCH

As analysis technology advances and equipment accuracy improves, humans have perfected a variety of planet detection techniques. These ways can be split into 2 main categories: indirect detection methods and methods of direct imaging. Indirect detection approaches comprise pulsar timing, astrometry, gravitational microlensing, arch astrolabe, radial velocity, transit method, orbital brightness adjustment method, planetary disk motion and remote sensing. This article will focus on three commonly used methods: radial velocity, transit, and direct imaging but not in the section. In this section, the study will introduce some common methods for discovering exoplanet and pertinent instrument briefly.

Astrometry is the earliest approach of finding for exoplanets. This method is to precisely locate the location of a star in the firmament and watch how that location alters over time. In case the star has a planet, the planet's gravity will lead to a star to move within a minuscule circular orbital. In this case, the stars and planets rotate round their widespread center of mass (the binary problem). Since the mass of a star is much enormous than that of a planet, its orbit is much marginal than that of a planet (Sahlmann and Fekel, 2013).

By observing the effects of exoplanets on a host star during their revolution, the timing method finds evidence of their presence. The pulsar's radiation emissions are very constant and fixed because of it revolve, because the revolve of a pulsar is steady in natural situation, so time anomaly detected on the radio wave radiation of the pulse is capable to calculate the motion of the pulsar. Owing to normal stars, pulsars move in small orbitals if they have planets. It is possible to compute and infer the orbital parameters from the pulsar's pulse time. The first exoplanet was discovered around the pulsar PSR 1257+12 (Wolszczan and Frail, 1992). The major disadvantage of the pulsar timing method is which pulsars are relatively unusual, so it is not possible to use this method to discover planets in large quantities. Meanwhile, as it known to all, life cannot exist on planets orbiting pulsars because of the very intense high-energy radiation.

Gravitational microlensing is a unique technique for discovering exoplanets as it is independent of the host star's brightness or the planetary system's orbita l motion. When a star's gravitational field acts like a lens, amplifying the light of a distant background star, the behavior of a gravitational microlensing is generated. This influence is only produced when the two stars are almost perfectly aligned. Only when the two stars move towards each other and the Earth are exactly in opposite positions, so the lensing event is short-lived and can only last for a few days or weeks. Thousands of such incidents have been located over the past decade. In case the star in the foreground has planets, then the lensing effect contributed by the planet's gravitational field can also be detected. Since this requires very precise alignment to detect the microgravitational lensing effect of the planets, it is vitally need to monitor a very large number of stars to have a reasonable chance of observing this phenomenon. The most likely outcome of this approach is to observe the stars that are situated between Earth and the Milky Way's core, which can provide a large number of background star. until the first discovery of microlensing planets in 2003, more than 200 planets have been identified by means of gravitational microlensing (Rektsini and Batistam 2024). This is the barely approach permissible of locating Earth-sized planets round ordinary main-sequence stars.

The Doppler brightening effect, in which the seen frequency deviates from the real frequency and the host star's brightness varies depending on the planet's radial velocity, can be brought on by the rotation of an exoplanet around the host star. An iconic example of the method is the NASA James Webb Space Telescope (JWST). It is called orbital brightness adjustment.

The planetary disk motion uses submillimeter light wave arrays to measure variations in the protoplanetary disk's substructure to infer the existence and development of exoplanets based on current hypotheses and observational data. One direct use of this technique is ALMA detection. Even though this technology has only been used to confirm one exoplanet thus far, the method's potential applications are growing and its future seems bright. Remote sensing is a popular technique for planet dis covery. Using equipment on the surface of ground, on satellites, or in the air, remote sensing methods collects data on planets and other celestial bodies. Seager and Deming summarized recent developments in the study of planetary atmospheres in their review paper. These advancements involved observations and models to disclose the properties of planetary atmospheres. For example, spectral features in planets' atmospheres can be observed, which is applicable to disclose the properties of planetary atmospheres through modeling and measurements (Seager and Deming, 2010).

## 3 PROBING BASED ON TRANSIT

The most practical and widely used method is the transit method; 4,115 exoplanets have been found using it. This is because detection projects like Kepler, K2, and TESS have developed successfully. The transit method's fundamental principal is to exploit the eclipse event, which occurs when a planet revolves around its primary star, and use satellites to track the main star's brightness drop to detect the presence of exoplanets. When a planet moves ahead of the star or blocks it, it is referred to by academics as a secondary eclipse. Primary eclipses occur when a planet passes in front of the star. The term "occultation depth" also refers to the primary star's degree of brightness drop. Because the brightness of the primary star in a secondary eclipse diminishes less, the existing detection methods only track the primary eclipse. The strengths of the light curve can be used for estimating a planet's size via the transit approach. Integrated with radial velocity, that can measure the mass of the planet, so the density of the planet can be determined, and then more information can be known about the physical structure of the planet. Nine of the known exoplanets have known their best characteristics through these two methods. Transit can also research the atmospheres of exoplanets. As the planet crosses in front of the star, the star's light passes through the planet's upper atmosphere. Researching the stellar spectrum of stars can identify the elements present in the atmosphere of the traveling star. It is also possible to measure the polarization of light as it travels through the atmosphere of the planet or is reflected by it, and to detect the composition of the planet's atmosphere and the planet's material.

Planets that Earth-like and are located in or surrounding to the Milky Way's habitable region, ranging in size from 0.5-2 times that of Earth. Kepler had discovered 2,778 exoplanets as of May 2013. To carry out the Kepler mission, K2, Kepler's second mission, was formally launched in May 2014

(Barclay, et al. 2018). Some typical results are shown in Fig. 2 (Yang, 2024).

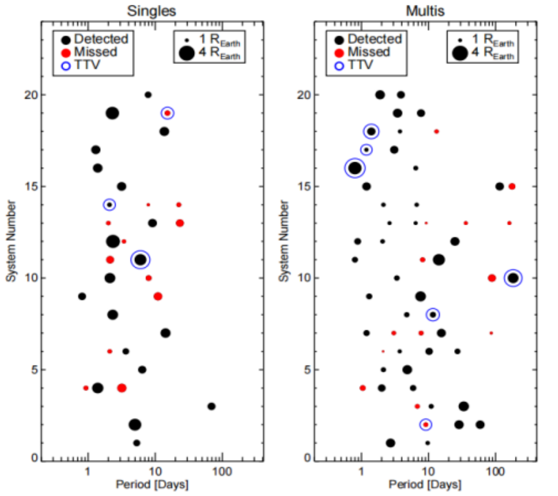


Figure 2: A sample for system that TESS discovered two or more transiting planet(right) a sample of M dwarf system that TESS found a single transiting planet (left) (Yang, 2024).

## 4 PROBING BASED ON RADIAL VELOCITY

Radial velocity, which is similar to astrometry, determines the velocity at which a star move closer or farther from the Earth by taking into account the fact that it moves in a brief circular orbit due to planet gravity. According to the Doppler effect, the radial velocity of a star can be determined by the motion of the spectral lines of the star. Once a star is in a basic two-body system, its orbital around the planet's mass center will be elliptical because of the planet's gravity, which causes some oscillation in the star. wave source and the observer change the wavelength of an object's radiation. When a star travels in a straight-line direction toward Earth, its lines will shift blue, and when it moves in the other direction, the spectral lines will shift red. The wave source's velocity as it moves toward the observation can be computed rely on the wave's degrees of red (or blue) shift. Using a spectrum analyzer mounted on a telescope, one can detect changes in spectral lines, or variations in a star's radius of variation or position over time, in order to identify the presence of exoplanets. The radial velocity approach, which yielded the initial exoplanet discovery, is very effective at finding planets in nearby and far-off star systems. One of the most significant strengths is that it permits the eccentricity in the planet's orbital to be calculated immediately. Although the radial velocity signal is not being influence of distance, high signal-to-noise-ratio spectra are necessary for high degree accuracy. A sketch is shown in Fig. 3.

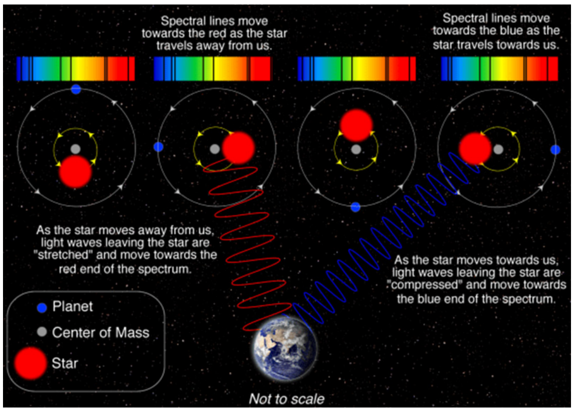


Figure 3: Diagram of Doppler effect in the 2-body systems (Zhou et al., 2024).

The James Webb Space Telescope (JWST), whose is launched in 2019, have a significant positive impact on exoplanet-hunting investigates by means of radial velocity. When this mission is in operation, it will use its sophisticated set of infrared instruments to measure the Doppler radii of stars in order to search for potential exoplanets.

## 5 PROBING BASED ON DIRECT IMAGING

The direct detection method can more precisely and thoroughly characterize the features of exoplanets, although it does require higher instrument accuracy, such as Gemini Planet Imager and VLT. Telescopes can only observe exoplanets with direct images under special circumstances. Specifically, direct images are only relatively easy to obtain when the planet is massive (usually much massive than Jupiter) and far enough away from the parent star to radiate a large amount of infrared light. Less false positives are one of the most evident benefits of using Direct Imaging. Although there aren't many possibilities to use this method, when direct detections can be made, it can give scientists crucial comprehensions on the planet. Astronomers can discover significant details about a planet's component, for example, by analyzing the wavelengths reflected by the atmosphere. The information is corresponding to exoplanet's characters and judge if it is potential for survival of human.

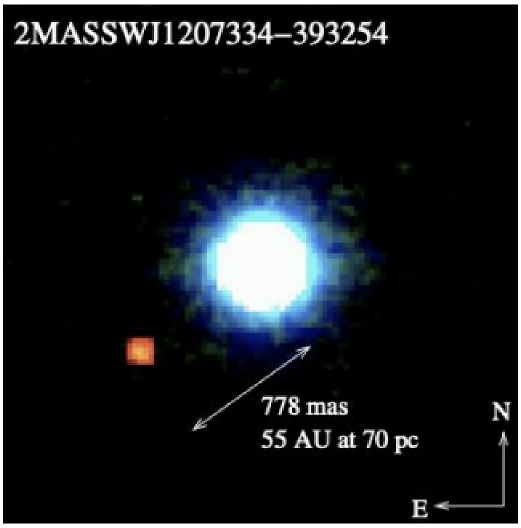


Figure 4: The CCD frame of 2M1207b [14].

On December 25, 2021, the James Webb Space Telescope (JWST) was launched into space, seen from Fig. 4 (Kalirai, 2018). NASA released the first direct image of the HIP 65426b obtained by JWST on September 1, 2022. Three dust rings were detected around this star, two of which were found for the first time. Water vapor was discovered by James Webb Space Telescope on July 24, 2023, near the region where rocky planets are formed. JWST detected carbon dioxide and methane in the atmosphere of K2-18b on September 11, 2013. With this assistance in the future, astronomers will still be able to study and understand the how the cosmos evolve, the formations and components of planet system, and the prospect of life in this system. In 1983, astronomer Edwin Powell Hubble received official recognition as the namesake of the Hubble Space Telescope (HST). After more than 40 years of planning, it was launched on April 24, 1990, from the Kennedy Space Center (KSC) in the America. A telescope in orbit surround the Earth. It is not affected by atmospheric turbulence because it is situated above Earth's atmosphere. It can detect ultraviolet light absorbed by the ozone layer and produces spectra and pictures that are remarkably steady and repeatable. The Hubble Space Telescope (HST) has altered the understanding of the universe and advanced the knowledge of it since its launch through the observation of data and photographs. Astronomers reported in 2001 that the STIS had effectively analyzed the exoplanet HD's atmosphere component (Debes et al., 2019). The exact mass of the Gliese 876b was found in 2002 with the aid of the Hubble Space Telescope. In 2008, Hubble detected carbon dioxide and methane on 2 exoplanets. In 2008, it took the first photo of an exoplanet. Hubble identify 7TRAPPIST-1 system elements in 2017. Liquid water was discovered on the outside of an exoplanet the size of Earth's atmosphere. In 2018, a potential exoplanet was discovered. The first detection of water vapor in the atmosphere of the exoplanet K2-18b occurred in 2019.

## 6 LIMITATIONS AND PROSPECTS

The exploration of exoplanets is a domain of great scientific value as it may help people find new homes in the future. However, currently, the major method of finding exoplanets are radial velocity, direct imaging, and transit methods; however, each of these methods has inherent drawbacks. Transit, for example, is unable to capture photos or gather spectral data on the planet itself. Only brief variations in light brought about by a planet moving in front of its parent stars can be detected by it. Extremely high telescope resolution and exact image processing are required for direct imaging of planets to divide them from the. Years of constant detections are needed for radial velocity to precisely calculate a planet's mass and orbit. Furthermore, powerful telescopes and devices are needed to find exoplanets. For example, to produce high-resolution and high-sensitivity photographs in darkness, direct imaging necessitates exceptionally high-performance telescopes and specialized equipment. With radial velocity, precision optometric devices and powerful computers are needed to estimate the planet masses and orbital characteristics. These reasons all lead us to only discover exoplanets that are relatively close to Earth, but unable to discover exoplanets that are farther away from us.

The study of exoplanets will face increasing possibilities as science and technology advance. More advanced instruments and methods of detection will be used in the future. The knowledge of the characteristics and evolution of exoplanets will increase owing to these novel instruments and methods for observation. Analyze the temperature, composition of the atmosphere, and alterations in climate of exoplanets to acquire a better comprehending of their ecology and evolution. Understanding the start and growth of life in else planet systems will be aided by this. Examine exoplanets' physical features, like mass, size, atmosphere, and surface structure, by spectroscopic or direct imaging methods. This will offer insights on the genesis and development of planets.

# 7 CONCLUSIONS

Overall, the space technology has advanced significantly because of scientific and technological advancements, it will have a crucial impact on the future development of human civilization. This study provides a comprehensive analysis and summary of the radial velocity, transit, and direct imaging techniques used in planetary exploration, along with information on their possible uses and limitations. Additionally, it describes a few additional widely used methods in finding exoplanets, include gravitational microlensing and astrometry. Even if there are still many challenges and barriers for humanity to solve, methods and advances in technology are constantly developing. Because it will increase the chances of surviving, improve the knowledge of the cosmos and the Earth, and have a significant impact on and alter the future, interstellar exploration holds immense importance for humanity. This work will offer some essential references for planetary exploration and research in the future.

# REFERENCES


Barclay, T., Pepper, J., Quintana, E. V., 2018. A revised exoplanet yield from the transiting exoplanet survey satellite (TESS). *The Astrophysical Journal Supplement Series*, 239(1), 2

Borucki, W. J., Koch, D., Basri, G., et al., 2010. Kepler planet-detection mission: introduction and first results. *Science*, 327(5968), 977-980.

Debes, J. H., Ren, B., Schneider, G., 2019. Pushing the limits of the coronagraphic occulters on Hubble space telescope/space telescope imaging spectrograph. Journal of Astronomical Telescopes, Instruments, and Systems, 5(3), 035003.

JWST group, 2023. Identification of carbon dioxide in an exoplanet atmosphere. *Nature*, 614(7949), 649-652.

Kalirai, J., 2018. Scientific discovery with the James Webb space telescope. Contemporary Physics, 59(3), 251-290.

Mamajek, E., Stapelfeldt, K., 2024. NASA Exoplanet Exploration Program (ExEP) Mission Star List for the Habitable Worlds Observatory 2023. *arxiv preprint* arxiv:2402.12414.

Mayor, M., Queloz, D., 1995. A Jupiter-mass companion to a solar-type star. *Nature*, 378(6555), 355-359.

Pepe, F., Molaro, P., Cristiani, S., 2014. ESPRESSO: The next European exoplanet hunter. *Astronomische Nachrichten*, 335(1), 8-20.

Rektsini, N. E., Batista, V., 2024. Finding planets via gravitational microlensing. *arXiv preprint* arXiv:2407.06689.

Sahlmann, J., Fekel, F. C., 2013. Astrometric mass ratios for three spectroscopic binaries. *Astronomy & Astrophysics*, 556, A145

Seager, S., Deming, D., 2010. Exoplanet atmospheres. *Annual Review of Astronomy and Astrophysics*, 48, 631-672.

Wolszczan, A., Frail, D. A., 1992. A planetary system around the millisecond pulsar psr1257 + 12. *Nature*, 355(6356), 145-147.

Yang, C., 2024. Analysis and Comparison of Three Exoplanet Searching Schemes. *Highlights in Science, Engineering and Technology*, 88, 914-921.

Yock, P., Muraki, Y., 2018. Microlensing Surveys for Exoplanet Research (MOA). *Handbook of Exoplanets*, 122.

Zhou, J., Xie, J., Ge, J., et al., JI, J., 2024. Progress on exoplanet detection and research in space. *Chinese Journal of Space Science*, 44(1), 5.